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16. Abstract

This report describes the sensitivity analysis performed on the Rigid Pavement Life-Cycle Cost Analysis program, a computer program developed by the Center for Transportation Research for the Texas Department of Transportation. The program predicts the performance and life-cycle cost of portland cement concrete pavements. The input variables of the program are identified, and their effect on life-cycle cost is quantified. The most sensitive variables are isolated and discussed.

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A SENSITIVITY ANALYSIS OF THE RIGID PAVEMENT LIFE-CYCLE COST ANALYSIS PROGRAM

by

Steven Michael Waalkes

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Research Report Number 0-1739-2

Research Project No. 0-1739

Life-Cycle Cost Analysis of Rigid Pavements

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

in cooperation with the

U.S. Department of Transportation

Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH

Bureau of Engineering Research

THE UNIVERSITY OF TEXAS AT AUSTIN

September 1999

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IMPLEMENTATION STATEMENT

This report describes the sensitivity analysis performed on the Rigid Pavement Life-Cycle Cost Analysis program, a computer program developed by the Center for Transportation Research. The program predicts the performance and life-cycle cost of portland cement concrete pavements. The input variables of the program are identified, and their effect on life-cycle cost is quantified. The most sensitive variables are isolated and discussed.

DISCLAIMERS

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Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

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CHAPTER 1. INTRODUCTION

The Rigid Pavement Life-Cycle Cost Analysis (RPLCCA) program is a computer program developed by Mr. Rob Harrison, Dr. W. James Wilde, and Dr. B. Frank McCullough, researchers at the Center for Transportation Research (CTR) at The University of Texas at Austin. The RPLCCA program is intended for use by the Texas Department of Transportation (TxDOT) in making decisions, based on life-cycle cost, regarding pavement alternatives for proposed highway construction projects. While the program, as it exists today, is able to calculate only the life-cycle cost of jointed reinforced concrete pavement (JRCP) and continuously reinforced concrete pavement (CRCP), it is set up to incorporate other types in the future.

1.1 BACKGROUND

TxDOT commissioned a research project in 1996 to promote life-cycle cost analysis of rigid pavements throughout TxDOT districts by developing a uniform methodology for performing life-cycle cost analysis that will eventually include all pavement types. The major objective of this project was to develop a comprehensive, modular life-cycle cost methodology that could evaluate existing and future projects. This objective was to include a framework for life-cycle cost analysis that was comprehensive and able to encompass all possible aspects of pavement design, agency costs, user costs, and other costs that are created as a consequence of a highway project. This framework was incorporated into a computer program dubbed the Rigid Pavement Life-Cycle Cost Analysis program, or RPLCCA.

1.1.1 Life-Cycle Cost Concepts

Life-cycle cost analysis allows state agencies to evaluate different alternatives to proposed highway projects based on the estimated or calculated life-cycle cost for each alternative. The American Association of State Highway Officials' (AASHO) "Red Book" first introduced the concept of life-cycle cost analysis (or cost-benefit analysis) to the broader highway construction arena in 1960. Also during the 1960s, two projects advanced the application of life-cycle cost principles to pavement design and pavement-type selection. The National Cooperative Highway Research Program (NCHRP) conducted a study under project NCHRP 1-10 to promote the concept of life-cycle cost analysis. Later, TxDOT funded a project to develop the rigid pavement system (RPS), which performs life-cycle cost analyses of rigid pavements and ranks alternate designs by total life-cycle cost.

The 1986 and the 1993 American Association of State Highway and Transportation Officials' (AASHTO) Pavement Design Guides encourage the concept of life-cycle costing and give detailed discussions about the various costs that should be considered in life-cycle cost analysis. Other countries, such as Canada, Australia, and Egypt, have also developed life-cycle cost analysis methodologies.

In 1991, the Intermodal Surface Transportation Efficiency Act (ISTEA) required "the use of life-cycle costs in the design and engineering of bridges, tunnels, or pavement" (Ref 1) in both metropolitan and statewide planning of surface transportation infrastructure. The reauthorization of ISTEA, the Transportation Equity Act for the 21st Century (TEA-21) (Ref 2), removes the requirement for life-cycle cost analysis on large highway projects. The TEA-21 legislation defines life-cycle cost analysis as "a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user costs, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment."

1.1.2 The Rigid Pavement Life-Cycle Cost Analysis Program

The RPLCCA program is a Windows-based computer program developed for TxDOT by CTR at The University of Texas at Austin. The RPLCCA program is a product of TxDOT Project 0-1739, which began in 1996 and concluded in 1999. The RPLCCA program requires the selection or specification of 138 input variables that are used to calculate the performance and life-cycle cost of rigid, or portland cement concrete, pavement alternatives.

The RPLCCA program calculates the present value of three types of costs in considering the total life-cycle cost for any pavement alternative: (1) Agency Cost, which is the cost to the agency (usually a state, county, city, or other type of governmental agency) for construction, maintenance, or rehabilitation of the pavement; (2) User Delay Cost, which is a dollar value assigned to the amount of time roadway users are delayed as a result of construction, maintenance, or rehabilitation activities; and (3) Vehicle Operating Cost, which is the amount of money spent by users of the facility on operating their vehicles during the facility's intended life. The RPLCCA program also calculates the amount of carbon monoxide (CO) emissions spewed forth from vehicle exhaust systems, as well as the number of accidents predicted for each pavement alternative over its intended lifetime.

1.1.3 Sensitivity Analyses

The current trend in engineering and design is the use of and reliance upon computer-based models to predict and compute the performance and cost of the designs specified. These types of models are usually based on empirical data, which in many cases can severely limit their applicability. If a model is developed from some finite set of data, then it might not work (or accurately predict) on some extreme data points. To use computer programming terminology, the "inference space" of the model is unknown owing to the limited amount of data from which it was derived.

Sensitivity analysis of the input variables in a model has become indispensable, both for determining the most influential variables in a program and for evaluating the reliability of the outputs. The traditional approach to sensitivity analysis, which is applied in this case, is to change one variable at a time, run the model/program, and record the output. This method is the so-called "ceteris paribus" method. Another approach to sensitivity analysis, taken by Mrawira et al. (Ref 3), is the Latin hypercube method. This approach accounts for interdependency of the inputs by selecting combinations of input variables instead of altering each input individually. This method was not chosen owing to the amount of time required to run the RPLCCA program, which is approximately 2 minutes per run (on average).

1.2 RESEARCH STUDY OBJECTIVES

The first objective of this research study was to decide upon three sets of input data for the RPLCCA program: one set of "medium" values, those values of input variables that are average input variables in the state of Texas; one set of "low" values, which are values of input variables that would most likely result in a *lower* life-cycle cost (compared to the medium); and a last set of "high" values, which would most likely result in a *higher* life-cycle cost (also compared to the medium). These three sets of input data would form boundaries for each input variable, outside of which any conclusions made from the sensitivity analysis might not hold true.

The second objective of this research study was to run the RPLCCA program with the medium set of data and alter each input variable individually to its corresponding high, and then low, value. The output of the program to be recorded was the total life-cycle cost, the user delay cost, and the performance of the specified pavement alternative in years.

The third objective of this research study was to analyze the data obtained from the runs with the RPLCCA program and then draw some conclusions regarding some of the input variables. These conclusions concern the sensitivity of each variable to certain outputs such as total life-cycle cost and pavement life, which will help establish the relative importance of each variable and assist designers with future revisions of the program. Recommendations are included based on the conclusions of the sensitivity analysis, as well as on user experience with the program.

CHAPTER 2. THE RPLCCA PROGRAM

Several components are necessary in the framework of a comprehensive life-cycle cost analysis program. The definition itself includes construction, maintenance, rehabilitation, social and economic impacts, and all other costs that can be attributed to the use, care, and maintenance of a pavement or other infrastructure component. The Rigid Pavement Life-Cycle Cost Analysis (RPLCCA) program includes as many of these as possible: construction, maintenance, rehabilitation, user delay, and vehicle-operating costs.

2.1 THE LIFE-CYCLE COST FRAMEWORK

In developing the framework for the RPLCCA program, the researchers studied and included, where appropriate, all aspects of pavement performance, rehabilitation, social and economic impacts, and public safety. Many of these components are neither fully understood nor easily calculated, yet an attempt to quantify and evaluate each aspect was made in developing the framework. The RPLCCA framework is the first attempt at including as many components of life-cycle cost as possible.

The first step in the framework is to determine the *initial cost* of the pavement alternative. This initial cost is based on such design inputs as pavement thickness, number of layers, aggregate type, and concrete properties.

The next step in the framework is to evaluate how well the pavement design alternative will perform over its intended lifetime. This evaluation is performed by predicting the distresses that will occur in the pavement at the end of each year in the lifetime of the pavement. If the distresses are severe enough to require attention, rehabilitation and maintenance activities will be specified and the associated costs will be calculated. In addition, the associated user costs (based on construction activities or work zones) and other external costs are calculated.

Figure 2.1 shows all the cost components that go into the life-cycle cost analysis framework. For each year that a pavement alternative is evaluated, the maintenance and rehabilitation routine in the computer program determines whether repair work is required and, if so, what the appropriate repair costs would be; associated user costs and external costs are calculated as well.

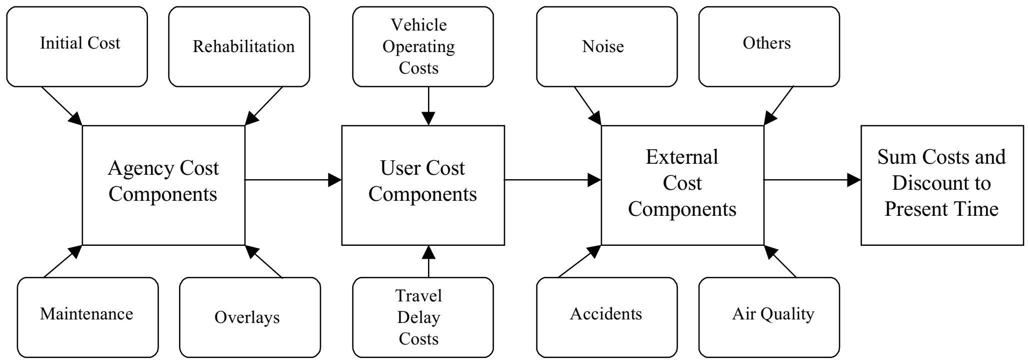

Figure 2.1. Cost Components of the Framework

Figure 2.2 graphically shows the framework of the program. It depicts each step in the program, as well as the components of each of the modules in the program.

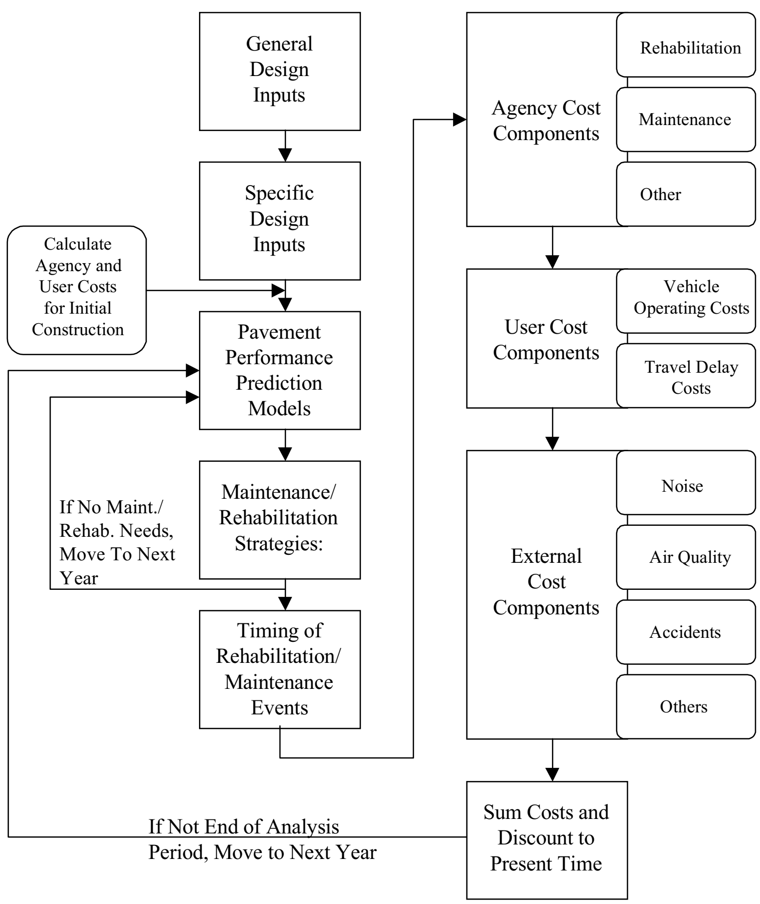

Figure 2.2. Comprehensive Life-Cycle Cost Analysis Framework

The life-cycle cost framework developed in this project predicts both agency and user costs over the expected life of a pavement design alternative, but, as in all cases, the final decision regarding the selection of a preferred alternative must rest on the shoulders of the engineer.

2.2 DESCRIPTION OF THE COMPUTER PROGRAM

The RPLCCA computer program was developed during the course of Research Project 0-1739. It is a Windows-based program, meaning that it has a graphical user interface and that it is also fairly self-explanatory and easy to use.

The user is required to enter project-level inputs, which apply to all the pavement design alternatives in the project, as well as alternative-specific inputs, which are individual to each specific alternative. In both cases, the inputs are grouped in specific screens, called “frames” or “tabs,” with other related input variables.

Once all the inputs have been specified, the user can run the analysis. There are two options in running the life-cycle cost analysis: The user can rely on the performance equations built into the program to predict when rehabilitation and maintenance activities need to be completed, **or** the user can decide (specify) when and over how much of the project to perform maintenance and rehabilitation activities. In the first case, the program is specifying maintenance activities and overlays automatically; in the second case, the program is being used only as a tool to calculate the total life-cycle cost.

CHAPTER 3. EXAMPLE APPLICATION

In order to understand how the Rigid Pavement Life-Cycle Cost Analysis (RPLCCA) program works, an example application will be shown in this chapter before the sensitivity analysis is discussed in the next few chapters. This example application will demonstrate how the program can be used in a typical situation in Texas. It will also showcase how the program's features and capabilities can be manipulated to provide maximum assistance to the program's user.

3.1 INTRODUCTION

This example application compares two very different construction methods for portland cement concrete (PCC) pavements: (1) precast slabs and (2) cast-in-place. The factors compared in this study relate strictly to the indirect costs to the users of a roadway during its construction or reconstruction. These indirect costs are normally quantified in terms of delay to the road user. This delay value can be calculated in terms of dollars per day with the assistance of the RPLCCA program. The module of the RPLCCA program that calculates user delay cost, the Queue and User Cost Evaluation of Work Zones (QUEWZ) module, can be isolated and used to predict only the user delay costs. The different input variables for each situation can be specified and fed into the QUEWZ module to compare the two types of construction. This comparison is initiated in order to quantify the amount of money saved in choosing a precast construction method over cast-in-place, because the actual construction costs for the precast method would most likely be greater.

3.2 EXAMPLE INPUTS

Because this is a conceptual example undertaken strictly to compare user delay costs between two types of pavement construction methods, a few assumptions were made:

1. Work zone / project length = 5 miles
2. Four-lane freeway, median separated, with frontage roads
3. Average daily traffic (ADT) = 50,000 vehicles per day
4. Vehicle mix: 25% trucks
5. One side of freeway reconstructed at a time

The 5-mile work zone was chosen as a possible average work zone length for medium-sized projects. The median-separated, four-lane freeway with frontage roads was chosen because it is the most common type of rural freeway found in Texas. The ADT of 50,000 vehicles per day (vpd) is a likely average for rural interstates in Texas, and the vehicle mix of 25% trucks is very common as well, because North American Free Trade Agreement (NAFTA) trade with Mexico is increasing the number of heavy trucks traveling on Texas highways.

In addition to those assumptions applicable to both construction methods, certain assumptions were needed for each of the methods. First, for the precast method:

1. To be constructed only at night
2. Traffic diverted only from 8 p.m. to 6 a.m.
3. Two traffic diversion strategies:
    a) Diversion to opposite side (one lane open in each direction)
    b) Diversion to frontage road; speed limit on frontage = 45 mph (one lane open for diverted traffic, two lanes open for opposite direction)

The precast method would be constructed only at night to reduce the traffic impacts of the construction. The precast slabs can be placed and anchored together during the night and have traffic running on them the very next morning. Therefore, the time of traffic diversion would occur only from 8 p.m. to 6 a.m. These two diversion strategies are very common in Texas.

For the cast-in-place method, only one assumption was needed. This construction method requires 24-hour traffic diversion, because the concrete needs time to set up and cure. The amount of actual work done might only be 10–12 hours a day, but the traffic diversion (one lane open in each direction) must be in place 24 hours a day.

3.3 DISCUSSION OF RESULTS

Three separate runs were made using the QUEWZ module of the RPLCCA program. First, the precast method with one lane open in each direction from 8 p.m. to 6 a.m., daily; second, the precast method with the work zone side diverted to the frontage road and the other side unchanged, also from 8 p.m. to 6 a.m.; and third, the cast-in-place method with one lane open in each direction, 24 hours a day.

Table 3.1 shows the user delay costs of the three methods, as calculated by the QUEWZ module of the RPLCCA program:

Table 3.1. Summary of Results for Example Application

Construction Method	Precast, 1-1	Precast, 2-1 (frontage)	Cast-in-place
User Delay Costs ***($/day)***	$1,810	$1,674	$383,714

The table clearly demonstrates that the precast construction methods present a much lower cost to the road users — a cost that is up to 230 times less expensive — representing a savings of $382,000. It should be noted, however, that this phenomenon does not apply strictly to precast construction methods. Any type of construction method that diverts traffic from 8 p.m. to 6 a.m. (in this scenario) will exhibit this much savings.

CHAPTER 4. THE SENSITIVITY ANALYSIS

This chapter details the design of the sensitivity analysis that was performed using the Rigid Pavement Life-Cycle Cost Analysis (RPLCCA) program. This program was developed by Dr. W. James Wilde as part of his doctoral dissertation, as well as part of a TxDOT–sponsored research project with the Center for Transportation Research, Project 0-1739. The computer program requires the input of 138 variables per pavement alternative, specified by the user, in order to perform the life-cycle cost calculations associated with each alternative. The purpose of the sensitivity analysis procedure is to isolate and show the effects of key variables of the RPLCCA program.

4.1 PRELIMINARY STEPS

As discussed in Section 1.1.3, sensitivity analyses are used to quantify the effects of input variables on computer models and programs. The RPLCCA program requires 138 input variables, selected and specified through a Windows-type graphical user interface. It was first thought that a complete sensitivity analysis of all 138 variables of the RPLCCA program would be exhausting and impractical, but the need to obtain a full factorial, or set of data, overcame any doubts about the time required to complete this.

A sensitivity analysis requires varying one input variable at a time, while the rest of the variables involved in the program are left constant at an average/medium value. An average value is defined as one that will generally be used in practice under normal design conditions. A "high" value is one, either high or low, which will produce a *high* life-cycle cost. Conversely, a "low" value is the high or low value of a variable that will produce a *low* life-cycle cost.

High, average, and low values selected for use in the sensitivity analysis were decided upon by: (1) consultation with experts, including Dr. B. Frank McCullough; (2) consultation with the program's designer, Dr. W. James Wilde; and (3) engineering judgment. These values were tabulated, and all 138 were used in the sensitivity analysis procedure.

4.2 PROCEDURE

The procedure for analyzing the input variables involved running the program repeatedly, keeping all values constant except for the one being analyzed. The input conditions are tabulated below (in Tables 4.1 and 4.2). The input variables are split into two different types: The first type is the project data variables and the second type is the alternative-specific variables. A particular pavement construction or reconstruction project will have certain characteristics that are the same, regardless of what type of pavement is constructed, so such things as loading characteristics, project geometry, and economic factors are grouped as *Project Variables.* Characteristics such as steel reinforcement and concrete properties are specific to each alternative, so they are considered *Alternative-Specific Variables*.

The end results of the program that were recorded for each type of pavement alternative — jointed reinforced concrete pavement (JRCP) and continuously reinforced concrete pavement (CRCP) — were: (1) the user delay cost, (2) the life-cycle cost, and (3) the life of the pavement, or year requiring overlay. These values were tabulated and scrutinized to identify any obvious patterns present in the data. The results are summarized in Chapter 5 and discussed in Chapter 6.

Table 4.1. Project-Level Input Variables

	Name	Description	Values High	Medium	Low	Units
1	InitUserCosts	consider initial user costs?	[redacted]	TRUE	FALSE	
2	TimeDelay	consider time delay?	[redacted]	TRUE	FALSE	
3	VOC	consider vehicle operating costs?	[redacted]	TRUE	FALSE	
4	Emissions	consider emissions?	[redacted]	TRUE	FALSE	
5	Accidents	consider accidents?	[redacted]	TRUE	FALSE	
6	Confidence	overall level of confidence	0.95	0.9	0.75	
7	Year1ESAL	first-year Equivalent Single- Axle Loads	1500000	500000	100000	ESALs
8	ESALGrowthRate	ESAL growth rate	8	3	1	%
9	AnalysisPeriod	analysis period	50	30	20	Years
10	Year1ADT	first-year ADT	100000	50000	20000	Vpd
11	LastYearADT	last-year ADT	300000	150000	60000	Vpd
12	TotalESALs	Total design ESALs (calculated)	67828275	22609425	4521885	ESALs
13	PercentTrucksIn	percent trucks	25	15	10	%
14	DiscountRate	discount rate	2.5	3.5	4.5	%
15	InterestRate	interest rate	3	5	15	%
16	InflationRate	inflation rate	10	2	1	%
17	ProjectLength	Total project length	20	5	0.5	Miles
18	TotalLanes	Total number of lanes	8	4	2	
19	InsideShldWidth	inside shoulder width	1	4	8	feet
20	LaneWidth	lane width	10	12	13	feet
21	OutsideShldWidth	outside shoulder width	6	10	12	feet
22	PCCProdRate	concrete paving production rate	200	250	300	SY/hour
23	ACPProdRate	asphalt paving production rate	300	375	500	SY/hour

Table 4.1 (continued). Project-Level Input Variables

	Name	Description	Values High	Medium	Low	Units
24	BCOCost	cost of bonded concrete overlay	70	40	30	$/SY-in
25	UBCOCost	cost of unbonded concrete overlay	40	30	22	$/SY-in
26	AnnMaintJRCPCost	cost of annual JRCP maintenance	6	4	2	$/SY
27	AnnMaintCRCPCost	cost of annual CRCP maintenance	5	3	1	$/SY
28	JtMaintCost	joint maintenance cost	12	8	4	$/lin. ft.
29	DowelRetroFit	dowel retrofitting cost	30	25	20	$/lin. ft.
30	DiamGrindCost	cost of diamond grinding	2	1.5	1.25	$/SY
31	PartDepthRepairCost	partial depth repair cost	190	150	110	$/SY
32	FullDepthRepairCost	full depth repair cost	110	100	90	$/SY
33	ShldrPatch	shoulder patch cost	70	50	40	$/SY
34	SpallPerDay	production rate: spall repair per day	150	200	250	SY/day
35	TCrackPerDay	production rate: crack repair per day	400	500	600	linear ft./day
36	FaultPerDay	production rate: fault repair per day	225	300	375	SY/day
37	Crossover	traffic control strategy for construction activities	SQUEEZE (11’)	CROSS	NOCROSS	
38	LaneNarrowWidth	narrow lane width	9	11	11.5	feet
39	UserCostCV	COV of user cost	30	20	10	
40	TotalInLanes	total number of lanes in one direction	4	2	1	
41	OpenlnLanes	total number of open lanes during work zone	3	1	1	

Table 4.1 (continued). Project-Level Input Variables

	Name	Description	Values High	Medium	Low	Units
42	WZLength	work zone length	22	6	1.5	miles
43	DivCriteria	diversion criteria: 1=length, 2=time, 3=no diversion	3	1	2	
44	DivLength	diversion length	30	8	3	miles
45	CritQLength	critical queue length	3	2	1	miles
46	CritQTime	critical queue time	30	20	10	min.
47	FreeFlowSpd	speed under free flow conditions	55	70	70	mph
48	Postedspd	posted work zone speed	45	55	65	mph
49	LOSDEBrkptSpd	speed at LOS D/E breakpoint	25	30	35	mph
50	QSpd	speed under queue conditions	2	10	15	mph
51	InCapBefWZ	lane capacity without work zone	1800	2000	2200	vphpl
52	InCapAftWZ	lane capacity with work zone	1385	1485	1585	vphpl
53	LOSDEVolIn	lane capacity at LOS D/E breakpoint	1550	1650	1750	vphpl
54	ADTIn	ADT	100000	50000	20000	vpd
55	FuncClass	functional class of roadway (11 = urban interstate)	11	11	1	
56	TimeTCSetup	time of traffic control setup	7	9	19	military time
57	TimeWorkBegin	time of work beginning	7	9	19	military time
58	TimeWorkEnd	time of work end	18	16	6	military time
59	TimeTCRemove	time of traffic control removal	18	16	6	military time
60	CarFuelCost	cost of passenger car fuel	1.40	1.10	0.90	$/gallon
61	CarTireCost	cost of passenger car tire	100	75	50	$/tire

Table 4.1 (continued). Project-Level Input Variables

	Name	Description	Values High	Medium	Low	Units
62	CarPrice	value of average passenger car	15000	10000	5000	$/vehicle
63	CarTimeValue	value of passenger car time	30	20	10	$/hour
64	TruckFuelCost	cost of truck fuel	1.30	1.10	0.85	$/gallon
65	TruckTireCost	cost of truck tire	300	250	200	$/tire
66	TruckPrice	value of avg. truck	150000	100000	50000	$/vehicle
67	TruckTimeValue	value of truck driver time	40	30	20	$/hour
68	OilPrice	cost of quart of oil	1.5	1.25	1	$/quart
69	NormAccRate	accident rate under normal conditions	3	2	1	accidents / million vehicles
70	WZAccRate	accident rate under work zone conditions	6	4	2	accidents / million vehicles
71	MaxAnnTemp	maximum annual temperature	110	100	90	deg. F
72	MinAnnTemp	minimum annual temperature	0	20	30	deg. F
73	Ave28DayTemps	average low temperature over 28 days after placement	90	70	60	deg. F
74	FreezeThawCycles	annual freeze-thaw cycles	10	2	1	
75	AnnRain	annual rainfall	50	30	10	in.
76	FaultLimit	max. faulting distress limit	0.1	0.15	0.2	in.
77	SpallLimit	max. spalling distress limit	15	25	35	% joints
78	CrackLimit	max. cracking distress limit	700	900	1100	cracks/mi.
79	PunchoutLimit	max. punchout distress limit	8	10	15	punch./mi.
80	PSILimit	minimum present serviceability index distress limit	3	2.5	2	PSI

Table 4.2. Alternative-Specific Input Variables

			Values			
	Name	**Description**	**High**	**Medium**	**Low**	**Units**
81	Drainage	drainage: 1=excellent, 5=very poor	4	2	1	
82	NumLayers	number of layers		3		
83	L1Type	material name for layer 1		PCC		
84	L1Thick	thickness of layer	8	10	12	in.
85	L1E	elastic modulus for layer 1	5000000	4500000	4000000	psi
86	L1Cost	cost of layer 1	95	85	75	$/CY
87	L1Poisson	Poisson’s ratio for layer 1	0.2	0.15	0.1	
88	L2Type	material name for layer 2		CTB		
89	L2Thick	thickness of layer	16	12	8	in.
90	L2E	elastic modulus for layer 2	750000	500000	250000	psi
91	L2Cost	cost of layer 2	80	70	60	$/CY
92	L2Poisson	Poisson’s ratio for layer 2	0.3	0.25	0.2	
93	L3Type	material name for layer 3		Granular		
94	L3Thick	thickness of layer	16	12	8	in.
95	L3E	elastic modulus for layer 3	100000	70000	40000	psi
96	L3Cost	cost of layer 3	70	60	50	$/CY
97	L3Poisson	Poisson’s ratio for layer 3	0.35	0.3	0.25	
98	SubgradeMod	modulus of subgrade reaction	100	200	300	psi/in.
99	Shrinkage	ultimate drying shrinkage	300	200	100	in/in
100	ConcAlpha	concrete coefficient of thermal expansion	7	5	3	in/in deg. F
101	TensStrength	tensile strength	400	500	600	psi
102	FlexStrength	flexural strength	500	600	700	psi

Table 4.2 (continued). Alternative-Specific Input Variables

	Name	Description	Values High	Medium	Low	Units
103	CompStrength	compressive strength	4000	4500	5000	psi
104	TiedEdge	tied concrete shoulder?	FALSE	TRUE		
105	FatigA	fatigue parameter A	2000000	4800000	7600000	
106	FatigB	fatigue parameter B		4		
107	MvtSliding	movement at sliding	0.01	0.015	0.02	in.
108	MaxFrictionForct	maximum friction force	4.5	3	1.5	psi
109	PercentLongReinf	percent longitudinal reinforcement	0.4 0.55	0.35 0/5	0.3 0.45	JRCP CRCP
110	PercentTransReinf	percent transverse reinforcement	0.15	0.1	0.05	
111	LongBarDiam	longitudinal bar diameter	0.75	0.625	0.5	in.
112	TransBarDiam	transverse bar diameter	0.625	0.5	0.375	in.
113	SteelYieldStress	steel yield stress	50	60	70	ksi
114	JtSpace	joint spacing (JRCP only)	15	20	25	ft.
115	DowelDiam	dowel diameter (JRCP only)	0	1	1.5	in.
116	TensStrCV	coefficient of variance (COV) of tensile strength	30	20	10	
117	SlabThickCV	COV of slab thickness	30	20	10	
118	RoughnessCV	COV of roughness	30	20	10	
119	DistressCV	COV for distress modeling	30	20	10	
120	CureTemp	concrete curing temperature	100	90	80	deg. F
121	DaystoColdest	number of days until coldest temperature	20	50	100	days

Table 4.2 (continued). Alternative-Specific Input Variables

	Name	Description	Values High	Values Medium	Values Low	Units
122	TimeToTraffic	time until construction traffic is applied	7	14	21	days
123	PCCStiffAfterCracking	PCC stiffness after cracking failure	700000	750000	800000	psi
124	MinTimeBtwOverlay	minimum time between overlays	3	5	7	years
125	MaxTimeBtwOverlay	maximum time between overlays	6	10	10	years
126	MinRemainLife	minimum remaining life allowable	15	20	25	%
127	AllowTotalOLThick	allowable total overlay thickness	16	14	12	in.
128	UnbondedOverlays	consider unbonded overlays?	FALSE	TRUE		
129	BBOLStiff	bond breaker stiffness	150000	200000	250000	psi
130	BBOLPoisson	bond breaker Poisson ratio	0.5	0.45	0.4	
131	PCCOverlays	consider concrete overlays?	FALSE	TRUE		
132	PCCTrialThick	concrete overlay trial thickness	5	4	3	in.
133	PCCOLStiff	stiffness of concrete overlay	4000000	5000000	6000000	psi
134	PCCOLPoisson	Poisson ratio of concrete overlay	0.2	0.15	0.1	
135	ACPOverlays	consider asphalt overlays?	FALSE	TRUE		
136	ACPTrialThick	asphalt overlay trial thickness	5	4	3	in.
137	ACPOLStiff	stiffness of asphalt overlay	300000	400000	500000	psi
138	ACPOLPoisson	Poisson ratio of asphalt overlay	0.45	0.4	0.35	

CHAPTER 5. RESULTS

This chapter presents the results of the sensitivity analysis performed on the Rigid Pavement Life-Cycle Cost Analysis (RPLCCA) program. The outputs recorded from each run of the program were total life-cycle cost and user delay cost in U.S. dollars per square yard of pavement; an additional output included the predicted life of the pavement alternative before an overlay (asphalt or concrete) was required. The results from both types of pavement structures are presented (in tabular form) first, followed by the sensitivity (in percent change) for each input variable.

5.1 RESULTS FROM AVERAGE VALUES

All of the data obtained by running the RPLCCA program using the high and low values for each input variable need to be compared to one average run. Accordingly, the average (medium) values for each variable were specified for both rigid pavement types, with the outputs then recorded. The program was run twenty-one times so that an average value for the continuously reinforced concrete pavement (CRCP) results could be obtained. The performance prediction models for the CRCP in the RPLCCA program are statistically based on an equation that requires a random-number seed for the pseudorandom-number generator. Thus, the end result using a one-tailed test will be within the specified confidence level. The results from the "average" run are found below in Table 5.1.

Table 5.1. Results from Average Run

	JRCP	CRCP*
User Delay Cost, $/SY	189.77	12.33
Total Life-Cycle Cost, $/SY	692.03	192.96
Overlay Year	24	28

* CRCP results are an average of twenty-one consecutive runs.

Table 5.2, below, lists the results obtained from running the CRCP average input values for the twenty-one consecutive runs.

Table 5.2. Calculation of Average for CRCP Alternative

Run No.	Delay Cost	Total LCC	Pavement Life
1	11.81	191.34	28
2	11.98	191.78	28
3	11.81	191.36	28
4	11.98	191.81	28
5	9.49	184.84	28
6	11.98	191.78	28
7	9.49	184.84	28
8	11.81	191.37	28
9	11.98	191.78	28
10	9.49	184.84	28
11	15.89	204.08	26
12	14.89	200.56	27
13	11.81	191.33	28
14	14.84	200.45	27
15	9.49	184.84	28
16	12.63	194.3	27
17	11.81	191.36	28
18	14.41	198.6	28
19	11.98	191.78	28
20	14.89	200.54	27
21	14.41	198.61	28
Average	12.33	192.96	27.7

5.2 TABULAR RESULTS

Because the RPLCCA program allows for two pavement types, and pavement type affects performance, it is expected that the same input values for the two different types will result in different outcomes. This is exactly the case with the RPLCCA program; there are two different performance equations built into the model — one for jointed reinforced concrete pavement (JRCP) and another for CRCP. Therefore, the same input values were used in both situations, with three exceptions: Because a CRCP does not have joints, the joint spacing and joint-transfer-dowel diameter variables for this alternative will always be zero. Also, the steel percentages for JRCP and CRCP are different, with the inputs reflected as such.

5.2.1 Results for JRCP Alternative

Table 5.3 shows the results obtained from running the input variables on the JRCP alternative. The areas of the table that are shaded denote those variables that did not have high and/or low values, such as the first five, which can be only True or False. Others might be shaded because of average values for Texas that do not change, such as the number of layers in the pavement structure (NumLayers). It was decided that this variable would be kept constant at three, because almost all rigid pavements in Texas are built with only three layers (i.e., concrete, base, and subbase).

In addition to the shaded areas, some of the values under the column "Overlay Year" (which is synonymous with pavement life) have an "F" in front of them. This "F" represents failure under that condition (Low or High value for the specific variable). The program is currently set up to require that each pavement alternative lasts at least two-thirds of its design life (or analysis period). If this design life does not occur for some reason (for example, because of an extreme value for a certain key input variable), the program will stop calculating costs for that pavement alternative. So, the life-cycle cost calculations for those variables that "failed" at extreme values cannot be analyzed, because the calculations did not take place for the full analysis period (30 years). But, the year at failure *can* be analyzed to determine the effect that these "F" variables had on pavement performance.

The last abbreviation found in Tables 5.3 and 5.4 is "NR." This abbreviation indicates that the alternative for that set of conditions did not require an overlay (i.e., "not required") — the pavement lasted as long as (or longer than) the analysis period.

Table 5.3. JRCP Results of Sensitivity Analysis

JRCP							
Values		Delay Cost ($/SY)		Total LCC ($/SY)		Overlay Year	
	Name	High	Low	High	Low	High	Low
1	InitUserCosts	[redacted]	189.77	[redacted]	692.03	[redacted]	24
2	TimeDelay	[redacted]	0	[redacted]	215.34	[redacted]	24
3	VOC	[redacted]	189.77	[redacted]	405.12	[redacted]	24
4	Emissions	[redacted]	189.77	[redacted]	692.03	[redacted]	24
5	Accidents	[redacted]	189.77	[redacted]	692.03	[redacted]	24
6	Confidence	138.26	166.97	506.66	607.87	F - 18	NR
7	Year1ESAL	72.01	178.89	301.73	641.16	F - 10	NR
8	ESALGrowthRate	72.01	188.05	307.11	683.99	F - 12	29
9	AnalysisPeriod	178.89	178.89	624.45	624.44	F - 20	NR
10	Year1ADT	190.55	189.05	695.65	688.65	22	26
11	LastYearADT	189.41	190.96	690.31	697.56	25	21
12	TotalESALs	189.77	189.77	692.03	692.03	24	24
13	PercentTrucksIn	181.65	194.72	699.48	689.37	24	24
14	DiscountRate	213.86	169.21	774.95	621.86	24	24
15	InterestRate	258.94	77.1	932.02	315.86	24	24
16	InflationRate	575.96	179.92	2088.41	658.32	24	24
17	ProjectLength	189.42	187.27	691.18	684.09	24	24
18	TotalLanes	229.71	141.61	787.98	576.79	24	24
19	InsideShldWidth	204.97	172.89	728.23	651.81	24	24
20	LaneWidth	177.33	194.71	662.48	704.05	24	24
21	OutsideShldWidth	210.99	180.91	743.31	670.91	24	24
22	PCCProdRate	189.77	189.77	692.03	692.03	24	24
23	ACPProdRate	192.41	187.13	703.47	680.58	24	24
24	BCOCost	189.77	189.77	692.03	692.03	24	24
25	UBCOCost	189.77	189.77	692.03	692.03	24	24
26	AnnMaintJRCPCost	189.77	189.77	728.81	655.24	24	24
27	AnnMaintCRCPCost	189.77	189.77	692.03	692.03	24	24
28	JtMaintCost	189.77	189.77	692.03	692.03	24	24
29	DowelRetroFit	189.77	189.77	692.03	692.03	24	24
30	DiamGrindCost	189.77	189.77	692.03	692.02	24	24
31	PartDepthRepairCost	189.77	189.77	711.01	673.05	24	24
32	FullDepthRepairCost	189.77	189.77	692.03	692.03	24	24
33	ShldrPatch	189.77	189.77	692.03	692.03	24	24
34	SpallPerDay	248.95	153.68	834.11	605.37	24	24
35	TcrackPerDay	189.77	189.77	692.03	692.03	24	24

Table 5.3 (continued). JRCP Results of Sensitivity Analysis

JRCP							
Values		Delay Cost ($/SY)		Total LCC ($/SY)		Overlay Year	
	Name	High	Low	High	Low	High	Low
36	FaultPerDay	189.77	189.77	692.03	692.03	24	24
37	Crossover	195.2	195.2	698.1	698.1	24	24
38	LaneNarrowWidth	186.65	195.2	672.55	698.1	24	24
39	UserCostCV	193.17	194.99	690.08	689.26	24	24
40	TotalInLanes	286.33	174.38	752.1	675.15	24	24
41	OpenInLanes	8.39	195.2	344.37	698.1	24	24
42	WZLength	189.77	189.77	1181.16	554.46	24	24
43	DivCriteria	189.77	189.77	692.03	692.03	24	24
44	DivLength	189.77	189.77	878.28	649.7	24	24
45	CritQLength	275.93	86.93	795.24	576.6	24	24
46	CritQTime	189.77	189.77	692.03	692.03	24	24
47	FreeFlowSpd	189.77	189.77	689.68	692.03	24	24
48	Postedspd	189.77	189.77	691.9	692.04	24	24
49	LOSDEBrkptSpd	189.77	189.77	688.54	694.65	24	24
50	QSpd	189.77	189.77	1854.01	591.73	24	24
51	InCapBefWZ	192.92	181.3	697.63	728.93	24	24
52	InCapAftWZ	198.71	186.07	699.51	688.16	24	24
53	LOSDEVolIn	189.77	189.77	690.28	693.38	24	24
54	ADTIn	348.45	14.37	1203.6	303.46	24	24
55	FuncClass	189.77	167.99	692.03	713.33	24	24
56	TimeTCSetup	214.02	213.22	766.3	359.6	24	24
57	TimeWorkBegin	248.65	175.77	684.39	713.33	24	24
58	TimeWorkEnd	189.77	234.65	692.03	720.52	24	24
59	TimeTCRemove	207.09	33.94	754.08	311.42	24	24
60	CarFuelCost	189.77	189.77	693.38	691.13	24	24
61	CarTireCost	189.77	189.77	692.04	692.01	24	24
62	CarPrice	189.77	189.77	696.07	687.98	24	24
63	CarTimeValue	264.8	114.75	874.7	509.35	24	24
64	TruckFuelCost	189.77	189.77	693.12	690.66	24	24
65	TruckTireCost	189.77	189.77	692.06	692	24	24
66	TruckPrice	189.77	189.77	693.61	690.45	24	24
67	TruckTimeValue	203.01	176.53	720.97	663.08	24	24
68	OilPrice	189.77	189.77	692.13	691.92	24	24
69	NormAccRate	189.77	189.77	692.03	692.03	24	24
70	WZAccRate	189.77	189.77	692.03	692.03	24	24

Table 5.3 (continued). JRCP Results of Sensitivity Analysis

	JRCP						
	Values	**Delay Cost ($/SY)**		**Total LCC ($/SY)**		**Overlay Year**	
	Name	**High**	**Low**	**High**	**Low**	**High**	**Low**
71	MaxAnnTemp	252.39	159.27	867.29	606.89	24	24
72	MinAnnTemp	281.61	159.27	949.15	606.89	24	24
73	Ave28DayTemps	189.77	189.77	692.03	692.03	24	24
74	FreezeThawCycles	189.77	189.77	692.03	692.03	24	24
75	AnnRain	189.77	189.77	692.03	692.03	24	24
76	FaultLimit	189.77	189.77	692.03	692.03	24	24
77	SpallLimit	216.47	171.64	766.7	641.39	24	24
78	CrackLimit	189.77	189.77	692.03	692.03	24	24
79	PunchoutLimit	189.77	189.77	692.03	692.03	24	24
80	PSILimit	130.79	188.37	485.72	685.49	F - 18	28
81	Drainage	130.79	189.05	476.65	688.65	F - 14	26
82	NumLayers						
83	L1Type						
84	L1Thick	72.01	178.89	291.23	645.89	F - 8	NR
85	L1E	190.16	189.77	693.81	692.03	23	24
86	L1Cost	189.77	189.77	694.81	689.25	24	24
87	L1Poisson	189.77	189.77	692.03	692.03	24	24
88	L2Type						
89	L2Thick	189.77	189.77	699.81	684.25	24	24
90	L2E	189.77	189.77	692.03	692.03	24	24
91	L2Cost	189.77	189.77	695.36	688.69	24	24
92	L2Poisson	189.77	189.77	692.03	692.03	24	24
93	L3Type						
94	L3Thick	189.77	189.77	698.69	685.36	24	24
95	L3E	189.77	189.77	692.03	692.03	24	24
96	L3Cost	189.77	189.77	695.36	688.69	24	24
97	L3Poisson	189.77	189.77	692.03	692.03	24	24
98	SubgradeMod	190.96	189.05	697.56	688.65	21	26
99	Shrinkage	189.77	189.77	692.03	692.03	24	24
100	ConcAlpha	189.77	189.77	692.03	692.03	24	24
101	TensStrength	189.77	189.77	692.03	692.03	24	24
102	FlexStrength	130.79	178.89	476.65	641.16	F - 14	NR
103	CompStrength	189.77	189.77	692.03	692.03	24	24
104	TiedEdge	130.79		479.04		F - 15	
105	FatigA	189.77	189.77	692.03	692.03	24	24

Table 5.3 (continued). JRCP Results of Sensitivity Analysis

	JRCP						
	Values	**Delay Cost ($/SY)**		**Total LCC ($/SY)**		**Overlay Year**	
	Name	**High**	**Low**	**High**	**Low**	**High**	**Low**
106	FatigB						
107	MvtSliding	189.77	189.77	692.03	692.03	24	24
108	MaxFrictionForct	189.77	189.77	692.03	692.03	24	24
109	PercentLongReinf	189.77	189.77	692.03	692.03	24	24
110	PercentTransReinf	189.77	189.77	692.03	692.03	24	24
111	LongBarDiam	189.77	189.77	692.03	692.03	24	24
112	TransBarDiam	189.77	189.77	692.03	692.03	24	24
113	SteelYieldStress	189.77	189.77	692.03	692.03	24	24
114	JtSpace	248.95	153.68	857.83	591.14	24	24
115	DowelDiam	13721.4	189.77	33309	692.02	24	24
116	TensStrCV	189.77	189.77	692.03	692.03	24	24
117	SlabThickCV	189.77	189.77	692.03	692.03	24	24
118	RoughnessCV	189.77	189.77	692.03	692.03	24	24
119	DistressCV	189.77	189.77	692.03	692.03	24	24
120	CureTemp	189.77	189.77	692.03	692.03	24	24
121	DaystoColdest	189.77	189.77	692.03	692.03	24	24
122	TimeToTraffic	189.77	189.77	692.03	692.03	24	24
123	PCCStiffAfterCracking	189.77	189.77	692.03	692.03	24	24
124	MinTimeBetweenOverlay	189.77	189.77	692.03	692.03	24	24
125	MaxTimeBetweenOverlay	189.77	189.77	692.03	692.03	24	24
126	MinRemainLife	189.77	189.77	692.03	692.03	24	24
127	AllowTotalOLThick	189.77	189.77	692.03	692.03	24	24
128	UnbondedOverlays	189.77		692.03		24	
129	BBOLStiff	189.77	189.77	692.03	692.03	24	24
130	BBOLPoisson	189.77	189.77	692.03	692.03	24	24
131	PCCOverlays	189.77		692.03		24	
132	PCCTrialThick	189.77	189.77	692.03	692.03	24	24
133	PCCOLStiff	189.77	189.77	692.03	692.03	24	24
134	PCCOLPoisson	189.77	189.77	692.03	692.03	24	24
135	ACPOverlays	203.2		754.34		24	
136	ACPTrialThick	189.77	189.77	692.03	692.03	24	24
137	ACPOLStiff	189.77	189.77	692.03	692.03	24	24
138	ACPOLPoisson	189.77	189.77	692.03	692.03	24	24

5.2.2 Results for CRCP Alternative

Table 5.4 displays the results of the sensitivity analysis for the CRCP alternative. Note that the abbreviations (and their associated conditions) found in Table 5.3 are applicable to Table 5.4 as well.

Table 5.4. CRCP Results of Sensitivity Analysis

CRCP							
Values		Delay Cost ($/SY)		Total LCC ($/SY)		Overlay Year	
	Name	High	Low	High	Low	High	Low
1	InitUserCosts		14.41		198.6		28
2	TimeDelay		0		144.65		28
3	VOC		11.81		156.45		28
4	Emissions		11.98		191.78		28
5	Accidents		14.41		198.6		28
6	Confidence	11.27	4.59	193.16	153.37	23	NR
7	Year1ESAL	0	0	105.6	140.51	F - 12	NR
8	ESALGrowthRate	3.96	2.17	124.07	146.6	F - 15	NR
9	AnalysisPeriod	2.85	0	139.22	123.79	F - 24	NR
10	Year1ADT	14.98	9.17	200.82	183.34	27	29
11	LastYearADT	11.98	9.82	191.77	186.39	28	27
12	TotalESALs	11.81	11.81	191.37	191.36	28	28
13	PercentTrucksIn	11.24	14.92	192.81	198.21	28	28
14	DiscountRate	12.45	9.21	208.84	171.42	28	28
15	InterestRate	28.37	1.87	285.58	104.77	28	28
16	InflationRate	124.15	12.78	845	187.91	28	28
17	ProjectLength	11.86	10.89	191.48	187.49	28	28
18	TotalLanes	12.49	11.65	193.05	191.37	28	28
19	InsideShldWidth	14.71	9.63	199.08	185.43	28	28
20	LaneWidth	12.24	11.77	192.88	191.32	28	28
21	OutsideShldWidth	12.42	14.23	193.14	198.32	28	28
22	PCCProdRate	11.98	15.89	191.78	204.08	28	28
23	ACPProdRate	17.27	12.51	210.86	190.23	27	27
24	BCOCost	11.98	11.81	191.78	191.36	28	28
25	UBCOCost	11.98	11.81	191.81	191.33	28	28
26	AnnMaintJRCPCost	9.49	14.84	221.62	163.67	28	27
27	AnnMaintCRCPCost	14.41	9.49	198.6	184.84	28	28
28	JtMaintCost	11.81	14.41	191.37	198.6	28	28
29	DowelRetroFit	9.49	11.81	184.84	191.37	28	28
30	DiamGrindCost	14.41	11.81	198.6	191.36	28	28
31	PartDepthRepairCost	9.49	11.81	184.84	191.12	28	28
32	FullDepthRepairCost	11.81	11.98	191.36	191.78	28	28
33	ShldrPatch	14.41	9.49	198.6	184.84	28	28
34	SpallPerDay	12.65	14.93	193.41	201.79	28	26
35	TcrackPerDay	14.89	14.89	200.54	200.56	27	27

Table 5.4 (continued). CRCP Results of Sensitivity Analysis

	CRCP						
	Values	**Delay Cost ($/SY)**		**Total LCC ($/SY)**		**Overlay Year**	
	Name	**High**	**Low**	**High**	**Low**	**High**	**Low**
36	FaultPerDay	14.41	11.81	198.61	191.35	28	28
37	Crossover	15.06	14.89	199.59	199.18	28	28
38	LaneNarrowWidth	20.94	14.89	206.81	199.15	28	28
39	UserCostCV	12.11	9.89	191.07	184.49	28	28
40	TotalInLanes	0	16.69	146.96	197.65	28	27
41	OpenInLanes	0	15.06	146.96	199.6	28	28
42	WZLength	11.81	11.81	261.06	171.77	28	28
43	DivCriteria	14.41	9.49	198.6	184.84	28	28
44	DivLength	14.41	9.49	212.46	182.79	28	28
45	CritQLength	21.31	5.74	206.21	182.53	28	28
46	CritQTime	11.98	14.41	191.78	198.6	28	28
47	FreeFlowSpd	9.49	11.98	184.19	191.78	28	28
48	Postedspd	15.89	14.89	203.96	200.55	26	27
49	LOSDEBrkptSpd	14.89	14.41	199.99	199.01	27	28
50	QSpd	11.81	11.98	343.12	178.34	28	28
51	InCapBefWZ	11.85	11.86	188.46	197	28	28
52	InCapAftWZ	14.69	14.09	195.34	192.99	28	27
53	LOSDEVolIn	9.49	11.98	184.51	192.01	28	28
54	ADTIn	32.1	0	246.99	144.19	28	28
55	FuncClass	11.81	13.24	191.37	198.15	28	28
56	TimeTCSetup	12.31	15.05	192.81	189.46	28	28
57	TimeWorkBegin	9.49	11.78	184.84	192.08	28	28
58	TimeWorkEnd	15.89	16.16	204.08	201.35	26	27
59	TimeTCRemove	15.38	10.12	202.32	188.14	27	28
60	CarFuelCost	11.81	11.98	191.47	191.7	28	28
61	CarTireCost	11.81	11.98	191.36	191.81	28	28
62	CarPrice	11.81	9.49	191.63	184.59	28	28
63	CarTimeValue	20.71	5.74	221.27	169.19	27	28
64	TruckFuelCost	11.81	11.98	191.47	191.64	28	28
65	TruckTireCost	14.41	9.49	198.64	184.83	28	28
66	TruckPrice	11.98	15.89	191.87	203.96	28	26
67	TruckTimeValue	15.93	13.85	204.08	197.02	27	27
68	OilPrice	14.41	11.81	198.62	191.34	28	28
69	NormAccRate	11.98	11.81	191.78	191.36	28	28
70	WZAccRate	11.98	11.81	191.81	191.33	28	28

Table 5.4 (continued). CRCP Results of Sensitivity Analysis

		CRCP					
Values		Delay Cost ($/SY)		Total LCC ($/SY)		Overlay Year	
	Name	**High**	**Low**	**High**	**Low**	**High**	**Low**
71	MaxAnnTemp	9.49	14.84	184.84	200.45	28	27
72	MinAnnTemp	11.98	9.49	191.78	184.84	28	28
73	Ave28DayTemps	9.49	12.63	184.84	194.3	28	27
74	FreezeThawCycles	11.81	11.81	191.37	191.36	28	28
75	AnnRain	11.98	14.41	191.78	198.6	28	28
76	FaultLimit	9.49	11.98	184.84	191.78	28	28
77	SpallLimit	15.89	14.89	204.08	200.54	26	27
78	CrackLimit	14.89	14.41	200.56	198.61	27	28
79	PunchoutLimit	11.46	12.87	190.32	194.33	28	28
80	PSILimit	11.27	5.25	193.16	155.14	23	NR
81	Drainage	0	2.32	117.55	147.03	F - 17	NR
82	NumLayers						
83	L1Type						
84	L1Thick	0	0	95.49	145.23	F - 10	NR
85	L1E	12.63	9.17	194.22	183.34	27	29
86	L1Cost	11.81	11.81	194.15	188.58	28	28
87	L1poisson	11.98	14.41	191.78	198.6	28	28
88	L2Type						
89	L2Thick	9.49	11.98	192.62	184.01	28	28
90	L2E	15.89	14.89	204.08	200.54	26	27
91	L2Cost	14.89	14.41	203.89	195.27	27	28
92	L2Poisson	11.81	11.98	191.35	191.78	28	28
93	L3Type						
94	L3Thick	11.81	11.98	198.03	185.15	28	28
95	L3E	11.81	9.49	191.33	184.04	28	28
96	L3Cost	14.84	9.49	203.79	181.5	27	28
97	L3Poisson	11.98	11.98	191.78	191.78	28	28
98	SubgradeMod	10.52	14.09	189.66	197.11	25	29
99	Shrinkage	11.81	11.81	191.37	191.36	28	28
100	ConcAlpha	11.98	11.75	191.82	191.2	28	28
101	TensStrength	15.07	9.49	201.07	184.84	27	28
102	FlexStrength	3.89	0	116.43	140.51	F - 12	NR
103	CompStrength	14.41	11.81	198.61	191.35	28	28
104	TiedEdge	0		119.7		F - 18	
105	FatigA	22.33	9.49	224.86	184.84	22	28

Table 5.4 (continued). CRCP Results of Sensitivity Analysis

		CRCP					
Values		Delay Cost ($/SY)		Total LCC ($/SY)		Overlay Year	
	Name	High	Low	High	Low	High	Low
106	FatigB						
107	MvtSliding	11.81	9.49	191.33	184.84	28	28
108	MaxFrictionForct	14.84	9.49	200.45	184.84	27	28
109	PercentLongReinf	14.62	9.49	199.15	184.84	28	28
110	PercentTransReinf	14.41	9.49	198.6	184.84	28	28
111	LongBarDiam	9.49	13.74	184.84	199.42	28	24
112	TransBarDiam	11.98	14.41	191.78	198.6	28	28
113	SteelYieldStress	9.49	11.98	184.84	191.78	28	28
114	JtSpace						
115	DowelDiam						
116	TensStrCV	16.15	9.49	204.75	184.84	26	28
117	SlabThickCV	11.81	11.98	191.36	191.81	28	28
118	RoughnessCV	11.81	9.49	191.33	184.84	28	28
119	DistressCV	15.54	9.49	202.35	184.84	27	28
120	CureTemp	15.32	9.49	201.72	184.84	27	28
121	DaystoColdest	11.81	11.81	191.33	191.37	28	28
122	TimeToTraffic	14.17	9.49	197.99	184.84	28	28
123	PCCStiffAfterCracking	14.62	14.89	199.16	200.55	28	27
124	MinTimeBetweenOverlay	11.98	9.49	191.8	184.84	28	28
125	MaxTimeBetweenOverlay	9.49	11.81	184.84	191.36	28	28
126	MinRemainLife	14.41	9.49	198.6	184.84	28	28
127	AllowTotalOLThick	9.49	11.81	184.84	191.37	28	28
128	UnbondedOverlays	11.81		191.36		28	
129	BBOLStiff	11.98	14.41	191.78	198.6	28	28
130	BBOLPoisson	14.41	9.49	198.6	184.84	28	28
131	PCCOverlays	11.81		191.37		28	
132	PCCTrialThick	11.81	11.98	191.36	191.78	28	28
133	PCCOLStiff	14.41	9.49	198.6	184.84	28	28
134	PCCOLPoisson	11.98	15.89	191.78	204.08	28	26
135	ACPOverlays	26.2		252.9		28	
136	ACPTrialThick	9.49	11.81	184.84	191.37	28	28
137	ACPOLStiff	11.81	11.98	191.36	191.78	28	28
138	ACPOLPoisson	14.41	9.49	198.6	184.84	28	28

5.2.3 Sensitivity of Input Variables for JRCP Alternative

Once the results were obtained, the sensitivity in percent change (from the medium/average set of variables) was calculated for the high and low value of each variable. This calculation was performed simply by taking the difference between the specified and average results and then dividing by the average. Table 5.5 displays the sensitivities of each of the variables for the JRCP alternative.

Table 5.5. Sensitivity of Input Variables for JRCP Alternative

JRCP							
	Percent Change	Delay Cost ($/SY)		Total LCC ($/SY)		Overlay Year	
	Name	**High**	**Low**	**High**	**Low**	**High**	**Low**
1	InitUserCosts		0		0		0
2	TimeDelay		-100		-68.88		0
3	VOC		0		-41.46		0
4	Emissions		0		0		0
5	Accidents		0		0		0
6	Confidence	-27.14	-12.01	-26.79	-12.16	-25	>25
7	Year1ESAL	-62.05	-5.73	-56.40	-7.35	-58.33	>25
8	ESALGrowthRate	-62.05	-0.91	-55.62	-1.16	-50	20.83
9	AnalysisPeriod	-5.73	-5.73	-9.77	-9.77	-16.67	>25
10	Year1ADT	0.41	-0.38	0.52	-0.49	-8.33	8.33
11	LastYearADT	-0.19	0.63	-0.25	0.80	4.17	-12.5
12	TotalESALs	0	0	0	0	0	0
13	PercentTrucksIn	-4.28	2.61	1.08	-0.38	0	0
14	DiscountRate	12.69	-10.83	11.98	-10.14	0	0
15	InterestRate	36.45	-59.37	34.68	-54.36	0	0
16	InflationRate	203.50	-5.19	201.78	-4.87	0	0
17	ProjectLength	-0.18	-1.32	-0.12	-1.15	0	0
18	TotalLanes	21.05	-25.38	13.87	-16.65	0	0
19	InsideShldWidth	8.01	-8.89	5.23	-5.81	0	0
20	LaneWidth	-6.56	2.60	-4.27	1.74	0	0
21	OutsideShldWidth	11.18	-4.67	7.41	-3.05	0	0
22	PCCProdRate	0	0	0	0	0	0
23	ACPProdRate	1.39	-1.39	1.65	-1.65	0	0
24	BCOCost	0	0	0	0	0	0
25	UBCOCost	0	0	0	0	0	0
26	AnnMaintJRCPCost	0	0	5.31	-5.32	0	0
27	AnnMaintCRCPCost	0	0	0	0	0	0
28	JtMaintCost	0	0	0	0	0	0
29	DowelRetroFit	0	0	0	0	0	0
30	DiamGrindCost	0	0	0	-0.001	0	0
31	PartDepthRepairCost	0	0	2.74	-2.74	0	0
32	FullDepthRepairCost	0	0	0	0	0	0
33	ShldrPatch	0	0	0	0	0	0
34	SpallPerDay	31.19	-19.02	20.53	-12.52	0	0
35	TCrackPerDay	0	0	0	0	0	0

Table 5.5 (continued). Sensitivity of Input Variables for JRCP Alternative

	JRCP						
	Percent Change	**Delay Cost ($/SY)**		**Total LCC ($/SY)**		**Overlay Year**	
	Name	**High**	**Low**	**High**	**Low**	**High**	**Low**
36	FaultPerDay	0	0	0	0	0	0
37	Crossover	2.86	2.86	0.88	0.88	0	0
38	LaneNarrowWidth	-1.64	2.86	-2.81	0.88	0	0
39	UserCostCV	1.79	2.75	-0.28	-0.40	0	0
40	TotalInLanes	50.88	-8.11	8.68	-2.44	0	0
41	OpenInLanes	-95.58	2.86	-50.24	0.88	0	0
42	WZLength	0	0	70.68	-19.88	0	0
43	DivCriteria	0	0	0	0	0	0
44	DivLength	0	0	26.91	-6.12	0	0
45	CritQLength	45.40	-54.19	14.91	-16.68	0	0
46	CritQTime	0	0	0	0	0	0
47	FreeFlowSpd	0	0	-0.34	0	0	0
48	Postedspd	0	0	-0.02	0.00	0	0
49	LOSDEBrkptSpd	0	0	-0.50	0.38	0	0
50	QSpd	0	0	167.91	-14.49	0	0
51	InCapBefWZ	1.66	-4.46	0.81	5.33	0	0
52	InCapAftWZ	4.71	-1.95	1.08	-0.56	0	0
53	LOSDEVolIn	0	0	-0.25	0.20	0	0
54	ADTIn	83.62	-92.43	73.92	-56.15	0	0
55	FuncClass	0	-11.48	0	3.08	0	0
56	TimeTCSetup	12.78	12.36	10.73	-48.04	0	0
57	TimeWorkBegin	31.03	-7.38	-1.10	3.08	0	0
58	TimeWorkEnd	0	23.65	0	4.12	0	0
59	TimeTCRemove	9.13	-82.12	8.97	-55.00	0	0
60	CarFuelCost	0	0	0.20	-0.13	0	0
61	CarTireCost	0	0	0.00	0.00	0	0
62	CarPrice	0	0	0.58	-0.59	0	0
63	CarTimeValue	39.54	-39.53	26.40	-26.40	0	0
64	TruckFuelCost	0	0	0.16	-0.20	0	0
65	TruckTireCost	0	0	0.00	0.00	0	0
66	TruckPrice	0	0	0.23	-0.23	0	0
67	TruckTimeValue	6.98	-6.98	4.18	-4.18	0	0
68	OilPrice	0	0	0.01	-0.02	0	0
69	NormAccRate	0	0	0	0	0	0
70	WZAccRate	0	0	0	0	0	0

Table 5.5 (continued). Sensitivity of Input Variables for JRCP Alternative

	JRCP						
	Percent Change	Delay Cost ($/SY)		Total LCC ($/SY)		Overlay Year	
	Name	High	Low	High	Low	High	Low
71	MaxAnnTemp	33.00	-16.07	25.33	-12.30	0	0
72	MinAnnTemp	48.40	-16.07	37.15	-12.30	0	0
73	Ave28DayTemps	0	0	0	0	0	0
74	FreezeThawCycles	0	0	0	0	0	0
75	AnnRain	0	0	0	0	0	0
76	FaultLimit	0	0	0	0	0	0
77	SpallLimit	14.07	-9.55	10.79	-7.32	0	0
78	CrackLimit	0	0	0	0	0	0
79	PunchoutLimit	0	0	0	0	0	0
80	PSILimit	-31.08	-0.74	-29.81	-0.95	-25	16.67
81	Drainage	-31.08	-0.38	-31.12	-0.49	-41.67	8.33
82	NumLayers						
83	L1Type						
84	L1Thick	-62.05	-5.73	-57.92	-6.67	-66.67	>25
85	L1E	0.21	0	0.26	0	-4.17	0
86	L1Cost	0	0	0.40	-0.40	0	0
87	L1Poisson	0	0	0	0	0	0
88	L2Type						
89	L2Thick	0	0	1.12	-1.12	0	0
90	L2E	0	0	0	0	0	0
91	L2Cost	0	0	0.48	-0.48	0	0
92	L2Poisson	0	0	0	0	0	0
93	L3Type						
94	L3Thick	0	0	0.96	-0.96	0	0
95	L3E	0	0	0	0	0	0
96	L3Cost	0	0	0.48	-0.48	0	0
97	L3Poisson	0	0	0	0	0	0
98	SubgradeMod	0.63	-0.38	0.80	-0.49	-12.5	8.33
99	Shrinkage	0	0	0	0	0	0
100	ConcAlpha	0	0	0	0	0	0
101	TensStrength	0	0	0	0	0	0
102	FlexStrength	-31.08	-5.73	-31.12	-7.35	-41.67	>25
103	CompStrength	0	0	0	0	0	0
104	TiedEdge	-31.08		-30.78		-37.5	
105	FatigA	0	0	0	0	0	0

Table 5.5 (continued). Sensitivity of Input Variables for JRCP Alternative

		JRCP					
Percent Change		Delay Cost ($/SY)		Total LCC ($/SY)		Overlay Year	
	Name	**High**	**Low**	**High**	**Low**	**High**	**Low**
106	FatigB						
107	MvtSliding	0	0	0	0	0	0
108	MaxFrictionForct	0	0	0	0	0	0
109	PercentLongReinf	0	0	0	0	0	0
110	PercentTransReinf	0	0	0	0	0	0
111	LongBarDiam	0	0	0	0	0	0
112	TransBarDiam	0	0	0	0	0	0
113	SteelYieldStress	0	0	0	0	0	0
114	JtSpace	31.19	-19.02	23.96	-14.58	0	0
115	DowelDiam	7130.52	0	4713.24	-0.001	0	0
116	TensStrCV	0	0	0	0	0	0
117	SlabThickCV	0	0	0	0	0	0
118	RoughnessCV	0	0	0	0	0	0
119	DistressCV	0	0	0	0	0	0
120	CureTemp	0	0	0	0	0	0
121	DaystoColdest	0	0	0	0	0	0
122	TimeToTraffic	0	0	0	0	0	0
123	PCCStiffAfterCracking	0	0	0	0	0	0
124	MinTimeBetweenOverlay	0	0	0	0	0	0
125	MaxTimeBetweenOverlay	0	0	0	0	0	0
126	MinRemainLife	0	0	0	0	0	0
127	AllowTotalOLThick	0	0	0	0	0	0
128	UnbondedOverlays	0		0		0	
129	BBOLStiff	0	0	0	0	0	0
130	BBOLPoisson	0	0	0	0	0	0
131	PCCOverlays	0		0		0	
132	PCCTrialThick	0	0	0	0	0	0
133	PCCOLStiff	0	0	0	0	0	0
134	PCCOLPoisson	0	0	0	0	0	0
135	ACPOverlays	7.08		9.00		0	
136	ACPTrialThick	0	0	0	0	0	0
137	ACPOLStiff	0	0	0	0	0	0
138	ACPOLPoisson	0	0	0	0	0	0

5.2.4 Sensitivity of Input Variables for CRCP Alternative

Table 5.6 displays the sensitivities of each of the variables for the CRCP alternative. Note that for Delay Cost and Life-Cycle Cost (LCC), there is never a zero percent change, primarily because the result is never the same twice (or the same as the average run), owing to the fact that the performance equation utilizes a random-number generator.

Table 5.6. Sensitivity of Input Variables for CRCP Alternative

	CRCP						
	Percent Change	**Delay Cost ($/SY)**		**Total LCC ($/SY)**		**Overlay Year**	
	Name	**High**	**Low**	**High**	**Low**	**High**	**Low**
1	InitUserCosts		16.87		2.92		0
2	TimeDelay		-100		-25.04		0
3	VOC		-4.22		-18.92		0
4	Emissions		-2.84		-0.61		0
5	Accidents		16.87		2.92		0
6	Confidence	-8.60	-62.77	0.10	-20.52	-17.86	>7
7	Year1ESAL	-100	-100	-45.27	-27.18	-57.14	>7
8	ESALGrowthRate	-67.88	-82.40	-35.70	-24.03	-46.43	>7
9	AnalysisPeriod	-76.89	-100	-27.85	-35.85	-14.29	>7
10	Year1ADT	21.49	-25.63	4.07	-4.99	-3.57	3.57
11	LastYearADT	-2.84	-20.36	-0.62	-3.40	0	-3.57
12	TotalESALs	-4.22	-4.22	-0.82	-0.83	0	0
13	PercentTrucksIn	-8.84	21.01	-0.08	2.72	0	0
14	DiscountRate	0.97	-25.30	8.23	-11.16	0	0
15	InterestRate	130.09	-84.83	48.00	-45.70	0	0
16	InflationRate	906.89	3.65	337.91	-2.62	0	0
17	ProjectLength	-3.81	-11.68	-0.77	-2.83	0	0
18	TotalLanes	1.30	-5.52	0.05	-0.82	0	0
19	InsideShldWidth	19.30	-21.90	3.17	-3.90	0	0
20	LaneWidth	-0.73	-4.54	-0.04	-0.85	0	0
21	OutsideShldWidth	0.73	15.41	0.09	2.78	0	0
22	PCCProdRate	-2.84	28.87	-0.61	5.76	0	0
23	ACPProdRate	40.06	1.46	9.28	-1.41	-3.57	-3.57
24	BCOCost	-2.84	-4.22	-0.61	-0.83	0	0
25	UBCOCost	-2.84	-4.22	-0.60	-0.84	0	0
26	AnnMaintJRCPCost	-23.03	20.36	14.85	-15.18	0	-3.57
27	AnnMaintCRCPCost	16.87	-23.03	2.92	-4.21	0	0
28	JtMaintCost	-4.22	16.87	-0.82	2.92	0	0
29	DowelRetroFit	-23.03	-4.22	-4.21	-0.82	0	0
30	DiamGrindCost	16.87	-4.22	2.92	-0.83	0	0
31	PartDepthRepairCost	-23.03	-4.22	-4.21	-0.95	0	0
32	FullDepthRepairCost	-4.22	-2.84	-0.83	-0.61	0	0
33	ShldrPatch	16.87	-23.03	2.92	-4.21	0	0
34	SpallPerDay	2.60	21.09	0.23	4.58	0	-7.14
35	TCrackPerDay	20.76	20.76	3.93	3.94	-3.57	-3.57

Table 5.6 (continued). Sensitivity of Input Variables for CRCP Alternative

		CRCP					
	Percent Change	**Delay Cost ($/SY)**		**Total LCC ($/SY)**		**Overlay Year**	
	Name	**High**	**Low**	**High**	**Low**	**High**	**Low**
36	FaultPerDay	16.87	-4.22	2.93	-0.83	0	0
37	Crossover	22.14	20.76	3.44	3.22	0	0
38	LaneNarrowWidth	69.83	20.76	7.18	3.21	0	0
39	UserCostCV	-1.78	-19.79	-0.98	-4.39	0	0
40	TotalInLanes	-100	35.36	-23.84	2.43	0	-3.57
41	OpenInLanes	-100	22.14	-23.84	3.44	0	0
42	WZLength	-4.22	-4.22	35.29	-10.98	0	0
43	DivCriteria	16.87	-23.03	2.92	-4.21	0	0
44	DivLength	16.87	-23.03	10.11	-5.27	0	0
45	CritQLength	72.83	-53.45	6.87	-5.41	0	0
46	CritQTime	-2.84	16.87	-0.61	2.92	0	0
47	FreeFlowSpd	-23.03	-2.84	-4.54	-0.61	0	0
48	Postedspd	28.87	20.76	5.70	3.93	-7.14	-3.57
49	LOSDEBrkptSpd	20.76	16.87	3.64	3.14	-3.57	0
50	QSpd	-4.22	-2.84	77.82	-7.58	0	0
51	InCapBefWZ	-3.89	-3.81	-2.33	2.09	0	0
52	InCapAftWZ	19.14	14.27	1.23	0.02	0	-3.57
53	LOSDEVolIn	-23.03	-2.84	-4.38	-0.49	0	0
54	ADTIn	160.34	-100	28.00	-25.27	0	0
55	FuncClass	-4.22	7.38	-0.82	2.69	0	0
56	TimeTCSetup	-0.16	22.06	-0.08	-1.81	0	0
57	TimeWorkBegin	-23.03	-4.46	-4.21	-0.46	0	0
58	TimeWorkEnd	28.87	31.06	5.76	4.35	-7.14	-3.57
59	TimeTCRemove	24.74	-17.92	4.85	-2.50	-3.57	0
60	CarFuelCost	-4.22	-2.84	-0.77	-0.65	0	0
61	CarTireCost	-4.22	-2.84	-0.83	-0.60	0	0
62	CarPrice	-4.22	-23.03	-0.69	-4.34	0	0
63	CarTimeValue	67.96	-53.45	14.67	-12.32	-3.57	0
64	TruckFuelCost	-4.22	-2.84	-0.77	-0.68	0	0
65	TruckTireCost	16.87	-23.03	2.94	-4.21	0	0
66	TruckPrice	-2.84	28.87	-0.56	5.70	0	-7.14
67	TruckTimeValue	29.20	12.33	5.76	2.10	-3.57	-3.57
68	OilPrice	16.87	-4.22	2.93	-0.84	0	0
69	NormAccRate	-2.84	-4.22	-0.61	-0.83	0	0
70	WZAccRate	-2.84	-4.22	-0.60	-0.84	0	0

Table 5.6 (continued). Sensitivity of Input Variables for CRCP Alternative

	CRCP						
	Percent Change	Delay Cost ($/SY)		Total LCC ($/SY)		Overlay Year	
	Name	High	Low	High	Low	High	Low
71	MaxAnnTemp	-23.03	20.36	-4.21	3.88	0	-3.57
72	MinAnnTemp	-2.84	-23.03	-0.61	-4.21	0	0
73	Ave28DayTemps	-23.03	2.43	-4.21	0.69	0	-3.57
74	FreezeThawCycles	-4.22	-4.22	-0.82	-0.83	0	0
75	AnnRain	-2.84	16.87	-0.61	2.92	0	0
76	FaultLimit	-23.03	-2.84	-4.21	-0.61	0	0
77	SpallLimit	28.87	20.76	5.76	3.93	-7.14	-3.57
78	CrackLimit	20.76	16.87	3.94	2.93	-3.57	0
79	PunchoutLimit	-7.06	4.38	-1.37	0.71	0	0
80	PSILimit	-8.60	-57.42	0.10	-19.60	-17.86	>7
81	Drainage	-100	-81.18	-39.08	-23.80	-39.29	>7
82	NumLayers						
83	L1Type						
84	L1Thick	-100	-100	-50.51	-24.74	-64.29	>7
85	L1E	2.43	-25.63	0.65	-4.99	-3.57	3.57
86	L1Cost	-4.22	-4.22	0.62	-2.27	0	0
87	L1Poisson	-2.84	16.87	-0.61	2.92	0	0
88	L2Type						
89	L2Thick	-23.03	-2.84	-0.18	-4.64	0	0
90	L2E	28.87	20.76	5.76	3.93	-7.14	-3.57
91	L2Cost	20.76	16.87	5.66	1.20	-3.57	0
92	L2Poisson	-4.22	-2.84	-0.83	-0.61	0	0
93	L3Type						
94	L3Thick	-4.22	-2.84	2.63	-4.05	0	0
95	L3E	-4.22	-23.03	-0.84	-4.62	0	0
96	L3Cost	20.36	-23.03	5.61	-5.94	-3.57	0
97	L3Poisson	-2.84	-2.84	-0.61	-0.61	0	0
98	SubgradeMod	-14.68	14.27	-1.71	2.15	-10.71	3.57
99	Shrinkage	-4.22	-4.22	-0.82	-0.83	0	0
100	ConcAlpha	-2.84	-4.70	-0.59	-0.91	0	0
101	TensStrength	22.22	-23.03	4.20	-4.21	-3.57	0
102	FlexStrength	-68.45	-100	-39.66	-27.18	-57.14	>7
103	CompStrength	16.87	-4.22	2.93	-0.83	0	0
104	TiedEdge	-100		-37.97		-35.71	
105	FatigA	81.10	-23.03	16.53	-4.21	-21.43	0

Table 5.6 (continued). Sensitivity of Input Variables for CRCP Alternative

		CRCP					
Percent Change		Delay Cost ($/SY)		Total LCC ($/SY)		Overlay Year	
	Name	High	Low	High	Low	High	Low
106	FatigB						
107	MvtSliding	-4.22	-23.03	-0.84	-4.21	0	0
108	MaxFrictionForct	20.36	-23.03	3.88	-4.21	-3.57	0
109	PercentLongReinf	18.57	-23.03	3.21	-4.21	0	0
110	PercentTransReinf	16.87	-23.03	2.92	-4.21	0	0
111	LongBarDiam	-23.03	11.44	-4.21	3.35	0	-14.29
112	TransBarDiam	-2.84	16.87	-0.61	2.92	0	0
113	SteelYieldStress	-23.03	-2.84	-4.21	-0.61	0	0
114	JtSpace						
115	DowelDiam						
116	TensStrCV	30.98	-23.03	6.11	-4.21	-7.14	0
117	SlabThickCV	-4.22	-2.84	-0.83	-0.60	0	0
118	RoughnessCV	-4.22	-23.03	-0.84	-4.21	0	0
119	DistressCV	26.03	-23.03	4.87	-4.21	-3.57	0
120	CureTemp	24.25	-23.03	4.54	-4.21	-3.57	0
121	DaystoColdest	-4.22	-4.22	-0.84	-0.82	0	0
122	TimeToTraffic	14.92	-23.03	2.61	-4.21	0	0
123	PCCStiffAfterCracking	18.57	20.76	3.21	3.93	0	-3.57
124	MinTimeBetweenOverlay	-2.84	-23.03	-0.60	-4.21	0	0
125	MaxTimeBetweenOverlay	-23.03	-4.22	-4.21	-0.83	0	0
126	MinRemainLife	16.87	-23.03	2.92	-4.21	0	0
127	AllowTotalOLThick	-23.03	-4.22	-4.21	-0.82	0	0
128	UnbondedOverlays	-4.22		-0.83		0	
129	BBOLStiff	-2.84	16.87	-0.61	2.92	0	0
130	BBOLPoisson	16.87	-23.03	2.92	-4.21	0	0
131	PCCOverlays	-4.22		-0.82		0	
132	PCCTrialThick	-4.22	-2.84	-0.83	-0.61	0	0
133	PCCOLStiff	16.87	-23.03	2.92	-4.21	0	0
134	PCCOLPoisson	-2.84	28.87	-0.61	5.76	0	-7.14
135	ACPOverlays	112.49		31.06		0	
136	ACPTrialThick	-23.03	-4.22	-4.21	-0.82	0	0
137	ACPOLStiff	-4.22	-2.84	-0.83	-0.61	0	0
138	ACPOLPoisson	16.87	-23.03	2.92	-4.21	0	0

5.2.5 Rating of Variables

Each variable was rated one of five ratings based on its sensitivity or percent change, which was found in Tables 5.5 and 5.6. In addition to the five ratings, an additional category was created because of unexpected results. This category was named "O" for "Opposite," meaning that the variables either: (1) produced results counter to what was expected or intuitive or (2) produced expected results in one type of pavement alternative (e.g., JRCP) and opposite results in the other (e.g., CRCP). The ratings, along with the justification for assessing each, are found below in Table 5.7:

Table 5.7. Ratings Assessed for Each Input Variable

Symbol	Rating	Justification
VH	Very High	if performance (pavement life) changes
H	High	if total life-cycle cost changes 10% or more
M	Medium	if total life-cycle cost changes 5–10%
L	Low	if total life-cycle cost changes 5% or less
N	None	if no change
O	Opposite	if opposite from expected or one type to other

The following tables list the ratings of each variable, grouped by rating. First is Table 5.8, with a listing of the variables with a "Very High" sensitivity rating.

Table 5.8. Variables Rated "Very High"

"Very High" Sensitivity Variables	Description
Confidence	Overall Level of Confidence
Year1ESAL	First-Year Equivalent Single-Axle Loads
ESALGrowthRate	ESAL Growth Rate
AnalysisPeriod	Analysis Period
Year1ADT	First-Year Average Daily Traffic (for pavement loading calcs.)
PSILimit	Present Serviceability Index Lower Limit
Drainage	Drainage of Pavement Structure (excellent to very poor)
L1Thick	Thickness of Concrete (Layer 1 in pavement structure)
SubgradeMod	Modulus of Subgrade Reaction
FlexStrength	Flexural Strength of Concrete
TiedEdge	Tied Concrete Shoulder? (Yes/No)
FatigA	Fatigue Parameter A

Next is Table 5.9, which contains the variables rated "High" sensitivity.

Table 5.9. Variables Rated "High"

"High" Sensitivity Variables	Description
TimeDelay	Consider Time Delay? (Y/N)
VOC	Consider Vehicle Operating Costs? (Y/N)
DiscountRate	Discount Rate used for Present Value Analysis
InterestRate	Interest Rate used for Present Value Analysis
InflationRate	Inflation Rate used for Present Value Analysis
TotalLanes	Total Number of Lanes
ACPProdRate	Asphalt Concrete Paving Production Rate
AnnMaintJRCPCost	Cost of Annual JRCP Maintenance
SpallPerDay	Production Rate: Spall Repairs per Day
TotalInLanes	Total Number of Lanes in One Direction
OpenInLanes	Total Number of Open Lanes during Work Zone
WZLength	Work Zone Length
DivLength	Diversion / Optional Detour Length
CritQLength	Critical Queue Length before Diversion
QSpd	Speed under Queue Conditions
ADTIn	Average Daily Traffic (for traffic delay calcs.)
TimeTCSetup	Time of Traffic Control Setup, each day
TimeTCRemove	Time of Traffic Control Removal, each day
CarTimeValue	Value of Passenger Car Time
MaxAnnTemp	Maximum Annual Temperature
MinAnnTemp	Minimum Annual Temperature
JtSpace	Joint Spacing (JRCP only)
DowelDiam	Dowel Diameter (JRCP only)

Table 5.10, below, lists the "Medium" sensitivity variables.

Table 5.10. Variables Rated "Medium"

"Medium" Sensitivity Variables	Description
InsideShldWidth	Inside Shoulder Width
OutsideShldWidth	Outside Shoulder Width
LaneNarrowWidth	Narrow Lane Width (during construction activities)
FuncClass	Functional Class of Roadway (e.g., 11=urban interstate)
TimeWorkBegin	Time that Work Begins (each day)
TruckTimeValue	Value of Truck Driver Time
SpallLimit	Maximum Spalling Distress Limit
TensStrCV	Coefficient of Variance (COV) of Tensile Strength

Table 5.11 contains those variables with a "Low" sensitivity on life-cycle cost.

Table 5.11. Variables Rated "Low"

"Low" Sensitivity Variables	Description
PercentTrucksIn	Percentage of Trucks in Traffic Stream
ProjectLength	Total Project Length
PartDepthRepairCost	Partial Depth Repair Cost
Crossover	Traffic Control Strategy (squeeze, crossover, no crossover)
UserCostCV	COV of User Cost
FreeFlowSpd	Speed under Free Flow Conditions
Postedspd	Posted Work Zone Speed
LOSDEBrkptSpd	Speed at Level-of-Service D/E Breakpoint
InCapBefWZ	Lane Capacity without Work Zone
InCapAftWZ	Lane Capacity with Work Zone
LOSDEVolIn	Lane Capacity at Level-of-Service D/E Breakpoint
CarFuelCost	Cost of Passenger Car Fuel
CarTireCost	Cost of Passenger Car Tire
CarPrice	Value of Average Passenger Car
TruckFuelCost	Cost of Truck Fuel
TruckTireCost	Cost of Truck Tire
TruckPrice	Value of Average Truck
OilPrice	Cost of Quart of Oil
L1E	Elastic Modulus for Concrete Layer
L1Cost	Cost of Concrete Layer
L2Thick	Thickness of Layer 2 (Base)
L2Cost	Cost of Layer 2 (Base)
L3Thick	Thickness of Layer 3 (Subbase)
L3Cost	Cost of Layer 3 (Subbase)
ACPOverlays	Consider Asphalt Concrete Pavement Overlays? (Y/N)

Table 5.12 contains a list of variables that have no effect on life-cycle cost. These variables were given the "None" rating.

Table 5.12. Variables Rated "None"

"None" Sensitivity Variables	Description
InitUserCosts	Consider Initial User Costs? (Y/N)
Emissions	Consider Emissions? (Y/N)
Accidents	Consider Accidents? (Y/N)
TotalESALs	Total Design ESALs (calculated)
PCCProdRate	Portland Cement Concrete Paving Production Rate
BCOCost	Cost of Bonded Concrete Overlay
UBCOCost	Cost of Unbonded Concrete Overlay
AnnMaintCRCPCost	Cost of Annual CRCP Maintenance
JtMaintCost	Joint Maintenance Cost
DowelRetroFit	Dowel Retrofitting Cost
DiamGrindCost	Cost of Diamond Grinding
FullDepthRepairCost	Full Depth Repair Cost
ShldrPatch	Shoulder Patch Cost
TcrackPerDay	Production Rate: Crack Repair per Day
FaultPerDay	Production Rate: Fault Repair per Day
DivCriteria	Diversion Criteria (length, time, or no diversion)
CritQTime	Critical Queue Time
NormAccRate	Accident Rate under Normal Conditions
WZAccRate	Accident Rate under Work Zone Conditions
Ave28DayTemps	Average Low Temperature over 28 Days after Placement
FreezeThawCycles	Annual Freeze-Thaw Cycles
AnnRain	Annual Rrainfall
FaultLimit	Maximum Faulting Distress Limit
CrackLimit	Maximum Cracking Distress Limit
PunchoutLimit	Maximum Punchout Distress Limit
L1Poisson	Poisson's Ratio for Concrete Layer
L2E	Elastic Modulus for Layer 2 (Base)
L2Poisson	Poisson's Ratio for Layer 2 (Base)
L3E	Elastic Modulus for Layer 3 (Subbase)
L3Poisson	Poisson's Ratio for Layer 3 (Subbase)
Shrinkage	Ultimate Drying Shrinkage
ConcAlpha	Concrete Coefficient of Thermal Expansion
TensStrength	Tensile Strength
CompStrength	Compressive Strength
MvtSliding	Movement at Sliding
MaxFrictionForct	Maximum Friction Force
PercentLongReinf	Percent Longitudinal Reinforcement (different for CRCP)
PercentTransReinf	Percent Transverse Reinforcement

Table 5.12 (continued). Variables Rated "None"

"None" Sensitivity Variables	Description
LongBarDiam	Longitudinal Bar Diameter
TransBarDiam	Transverse Bar Diameter
SteelYieldStress	Steel Yield Stress
SlabThickCV	COV of Slab Thickness
RoughnessCV	COV of Roughness
DistressCV	COV for Distress Modeling
CureTemp	Concrete Curing Temperature
DaystoColdest	Number of Days until Coldest Temperature
TimeToTraffic	Time until Construction Traffic is Applied
PCCStiffAfterCracking	PCC Stiffness after Cracking Failure
MinTimeBetweenOverlay	Minimum Time between Overlays
MaxTimeBetweenOverlay	Maximum Time between Overlays
MinRemainLife	Minimum Remaining Life Allowable
AllowTotalOLThick	Allowable Total Overlay Thickness
UnbondedOverlays	Consider Unbonded Concrete Overlays?
BBOLStiff	Bond Breaker Stiffness
BBOLPoisson	Bond Breaker Poisson Ratio
PCCOverlays	Consider Portland Cement Concrete Overlays?
PCCTrialThick	PCC Overlay Trial Thickness
PCCOLStiff	Stiffness of PCC Overlay
PCCOLPoisson	Poisson Ratio of PCC Overlay
ACPTrialThick	Asphalt Concrete Pavement Overlay Trial Thickness
ACPOLStiff	Stiffness of ACP Overlay
ACPOLPoisson	Poisson Ratio of ACP Overlay

Table 5.13 lists the three variables that were rated as "Opposite." The first listed, LastYearADT, is the average daily traffic for the last year of the analysis. This variable is used in calculating the loads predicted to occur on the pavement over its lifetime. One would think that as this value increases, the life-cycle cost would increase as well, because more loading would cause more distresses in the pavement and most likely lead to reduced life. But in both types of pavement, JRCP and CRCP, the pavement life was reduced and the life-cycle costs increased when the low input value was used.

The second "Opposite" variable listed is LaneWidth. This variable had no effect on pavement life for both types of pavement, which is expected, but it increased life-cycle cost as it increased, which is unexpected. In addition, this second result occurred only in the

JRCP alternative. Usually wider lanes result in increased traffic flow and therefore reduce delay and operating costs, but this was not the case.

The last variable in Table 5.13 is TimeWorkEnd, which is the time when construction work would end each day that construction, maintenance, or rehabilitation activities are occurring on the project. As this value increased, the workday got longer; and while one would expect the life-cycle cost or delay cost to likewise increase, this was not the case. As the workday got longer, the delay and life-cycle cost decreased.

Table 5.13. Variables Rated "Opposite"

"Opposite" Sensitivity Variables	**Description**
LastYearADT	Last Year ADT (for pavement loading calcs.)
LaneWidth	Lane Width
TimeWorkEnd	Time of Work End (each day)

5.2.6 Sensitivity of Selected Overlay Option

In addition to determining the sensitivity of almost all of the 138 input variables, the sensitivity of the program to the selected overlay option was also calculated. Once the program determines that the pavement structure is beyond the point that maintenance activities can improve its condition, it will trigger an overlay. This brings up a dialog box asking the user to choose one of the ten standard overlay options contained in the program:

- 2-, 3-, 4-, 5-, and 6-inch Asphalt Concrete Pavement (ACP)
- 3-, 4-, 5-, 6-, and 7-inch Unbonded Concrete Overlay (UBCO)

For all of the runs on the input variables, only one type of overlay was specified each time, the 2-inch ACP, so that the results would all be comparable to the same average. But because there are ten different overlay types, it was decided that determining the sensitivity of these would be beneficial to the overall sensitivity analysis of the program. The results of selecting a different overlay are found below in Table 5.14.

Table 5.14. JRCP and CRCP Results from Changing Overlay Selection

	JRCP			CRCP		
Overlay Option	Delay Cost	Total LCC	Overlay Yr.	Delay Cost	Total LCC	Overlay Yr.
2 in. ACP	189.77	692.03	24	14.41	198.6	28
3 in. ACP	195.38	718.17	24	14.38	207.62	28
4 in. ACP	200.66	742.89	24	21.3	235.7	28
5 in. ACP	206.27	769.04	24	26.19	258.47	28
6 in. ACP	211.55	793.76	24	30.95	280.43	28
3 in. UBCO	203.3	754.34	24	26.2	252.9	28
4 in. UBCO	211.5	792.54	24	28.47	272.43	28
5 in. UBCO	219.8	830.74	24	38.14	312.66	28
6 in. UBCO	228.05	868.94	24	47.76	352.78	28
7 in. UBCO	235.97	905.71	24	52.07	377.57	28

The sensitivity was then calculated for each selection. The results for the JRCP alternative are in Table 5.15, and the results for the CRCP alternative in Table 5.16.

Table 5.15. Sensitivity of Selected Overlay Option — JRCP Alternative

	JRCP					
	Delay Cost		**Total LCC**		**Overlay Yr.**	
Overlay Option	Value	% Change	Value	% Change	Value	% Change
2 in. ACP	189.77	0	692.03	0	24	0
3 in. ACP	195.38	2.96	718.17	3.78	24	0
4 in. ACP	200.66	5.74	742.89	7.35	24	0
5 in. ACP	206.27	8.69	769.04	11.13	24	0
6 in. ACP	211.55	11.48	793.76	14.70	24	0
3 in. UBCO	203.3	7.13	754.34	9.00	24	0
4 in. UBCO	211.5	11.45	792.54	14.52	24	0
5 in. UBCO	219.8	15.82	830.74	20.04	24	0
6 in. UBCO	228.05	20.17	868.94	25.56	24	0
7 in. UBCO	235.97	24.35	905.71	30.88	24	0

Table 5.16. Sensitivity of Selected Overlay Option — CRCP Alternative

	CRCP					
	Delay Cost		**Total LCC**		**Overlay Yr.**	
Overlay Option	Value	% Change	Value	% Change	Value	% Change
2 in. ACP	12.33	0	192.96	0	28	0
3 in. ACP	14.38	16.63	207.62	7.60	28	0
4 in. ACP	21.3	72.75	235.7	22.15	28	0
5 in. ACP	26.19	112.41	258.47	33.95	28	0
6 in. ACP	30.95	151.01	280.43	45.33	28	0
3 in. UBCO	26.2	112.49	252.9	31.06	28	0
4 in. UBCO	28.47	130.90	272.43	41.18	28	0
5 in. UBCO	38.14	209.33	312.66	62.03	28	0
6 in. UBCO	47.76	287.35	352.78	82.83	28	0
7 in. UBCO	52.07	322.30	377.57	95.67	28	0

5.3 GRAPHICAL REPRESENTATION

In order to help visualize the effect that some of the key input variables have on life-cycle cost, charts and graphs will be included in this section. The slopes of the lines on the charts will help to explain the effect of the low and high levels of the input variables.

5.3.1 Selected Input Variables — JRCP Alternative

Figure 5.1 is an example of the effect that three input variables with a "Very High" sensitivity rating have on Total Life-Cycle Cost for JRCP.

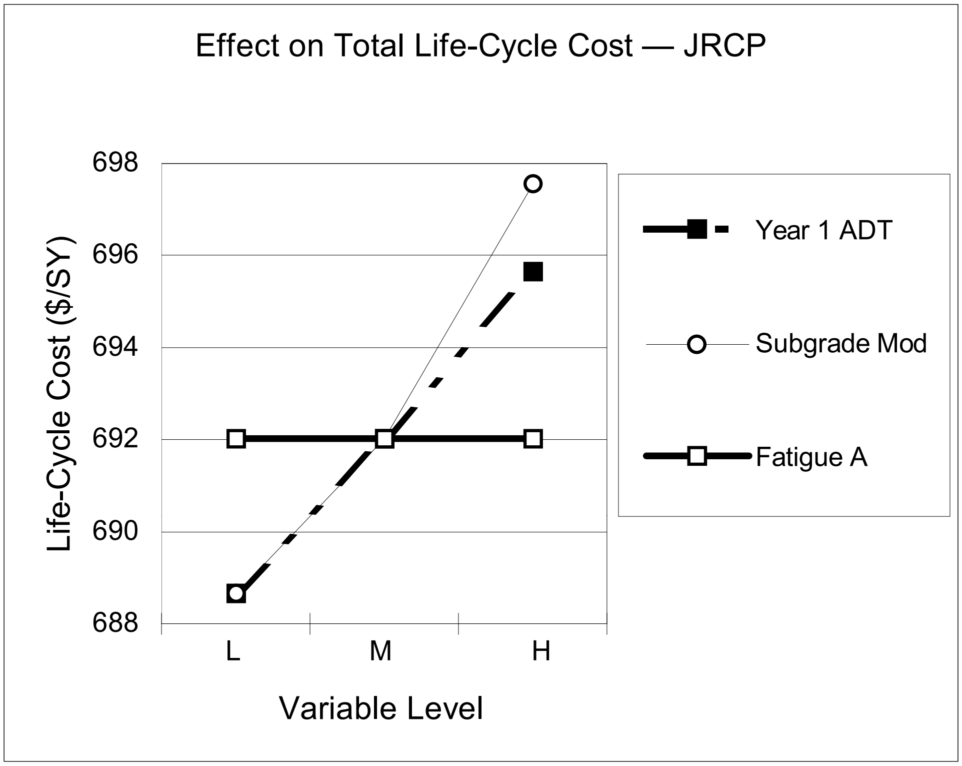

Figure 5.1. Effect of Year1ADT, SubgradeMod, and FatigueA on LCC — JRCP

Figure 5.2 shows the effect that those same three variables (from Figure 5.1) have on User Delay Cost, for JRCP alternatives.

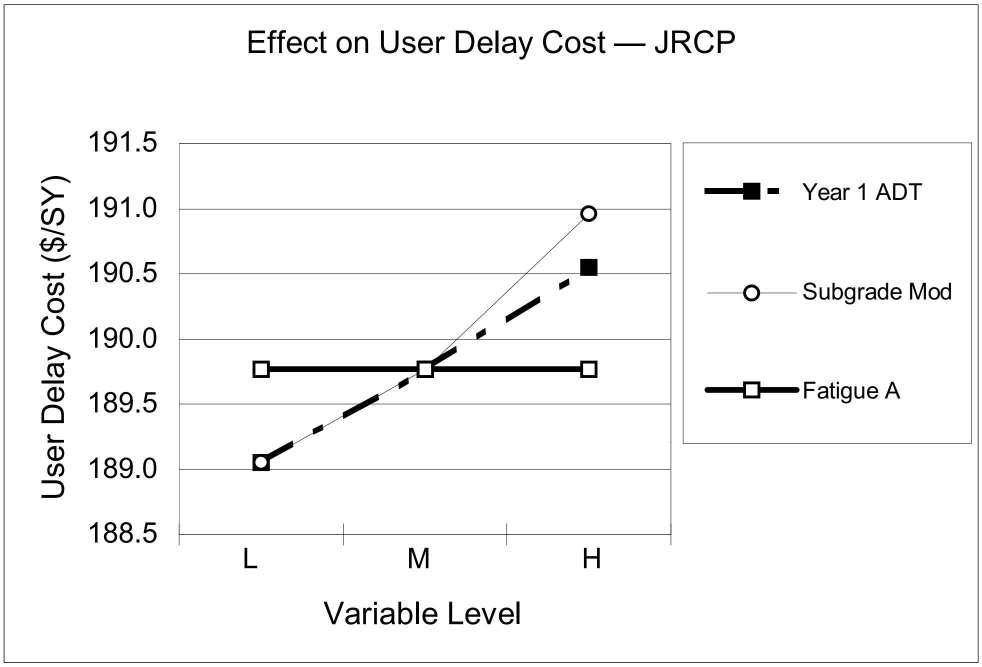

Figure 5.2. Effect of Year1ADT, SubgradeMod, and FatigueA on Delay — JRCP

Figure 5.3 is a plot of the Pavement Life (OverlayYear) versus Variable Level for the same three variables (Year1ADT, SubgradeMod, and FatigueA) and pavement type (JRCP).

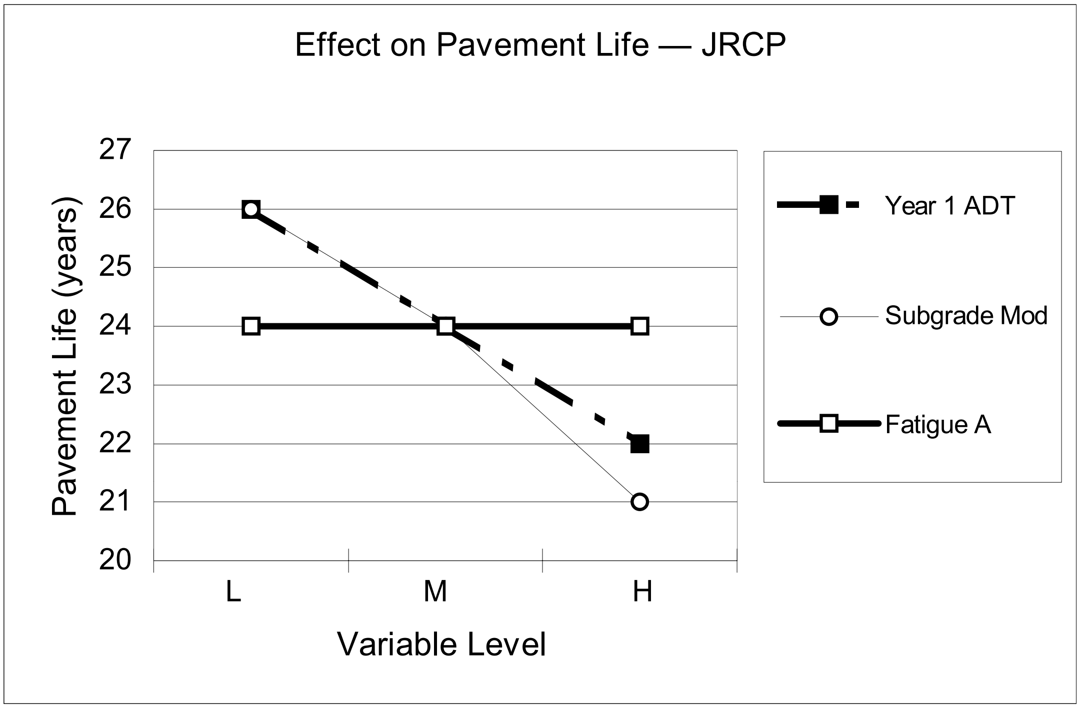

Figure 5.3. Effect of Year 1 ADT, Subgrade Mod, and Fatigue A on Life — JRCP

Figure 5.4 is a plot of five other variables that also have a "Very High" sensitivity rating. But these five variables are so sensitive that the pavement alternative failed before reaching two-thirds of its design life. So the life-cycle cost and delay cost results are not significant. Figure 5.4 is the only plot that shows the effect of these five variables on JRCP alternatives.

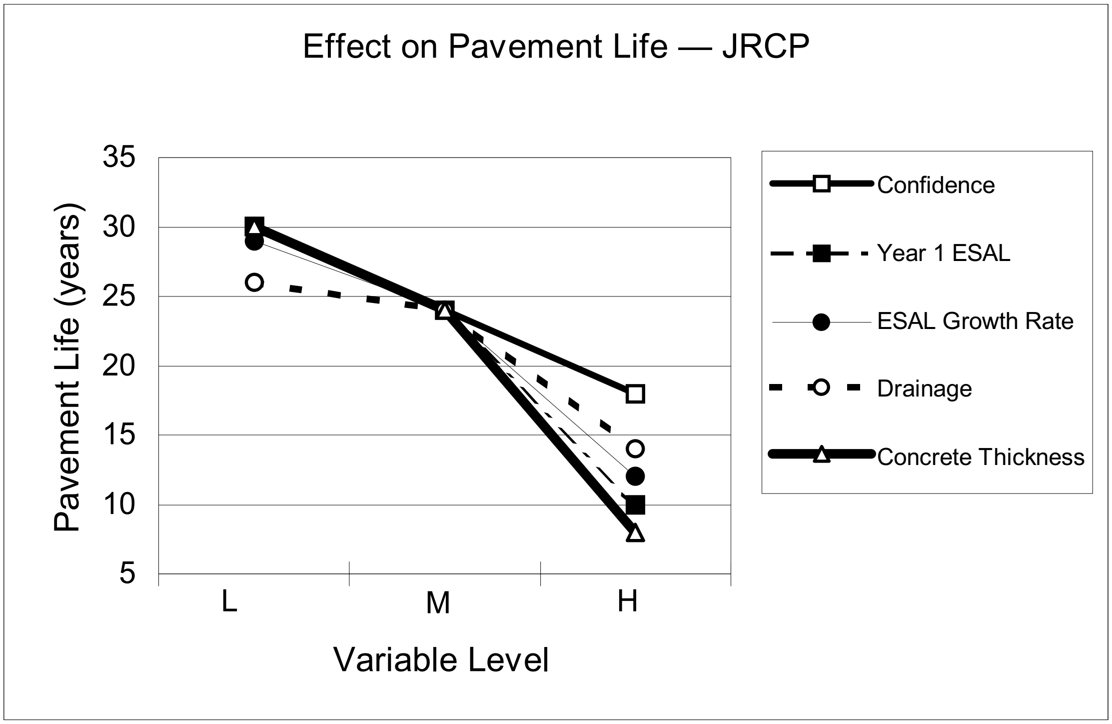

Figure 5.4. Effect of five "Very High" Variables on Pavement Life — JRCP

5.3.2 Selected Input Variables — CRCP Alternative

Figure 5.5 is an example of the effect that three input variables with a "Very High" sensitivity rating have on Total Life-Cycle Cost for JRCP.

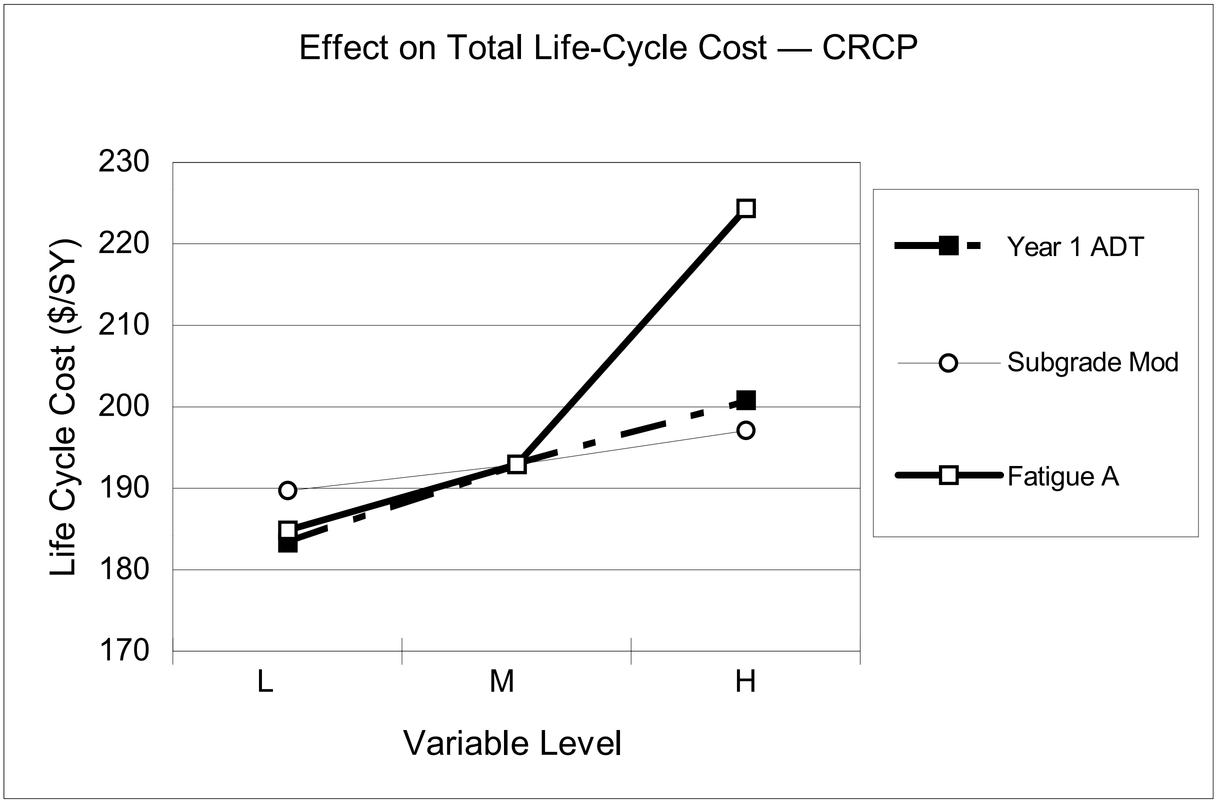

Figure 5.5. Effect of Year1ADT, SubgradeMod, and FatigueA on LCC — CRCP

Figure 5.6 shows the effect that those same three variables (from Figure 5.1) have on User Delay Cost for CRCP alternatives.

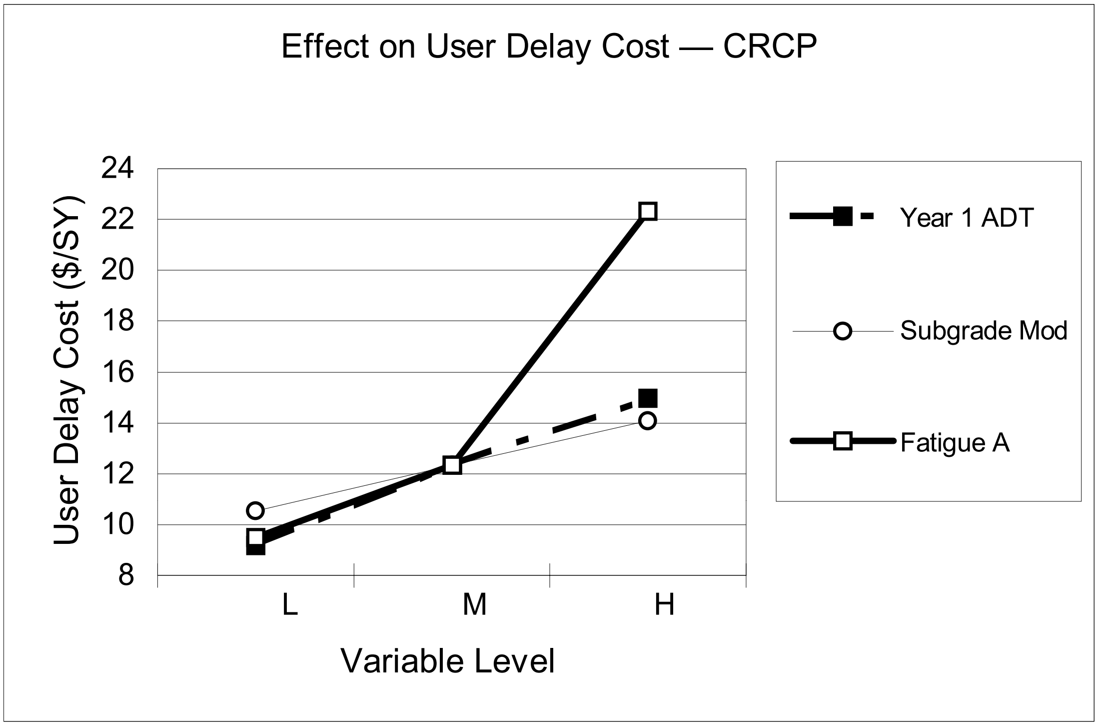

Figure 5.6. Effect of Year 1 ADT, Subgrade Mod, and Fatigue A on Delay — CRCP

Figure 5.7 is a plot of the Pavement Life (OverlayYear) versus Variable Level for the same three variables (Year1ADT, SubgradeMod, and FatigueA) and pavement type (CRCP).

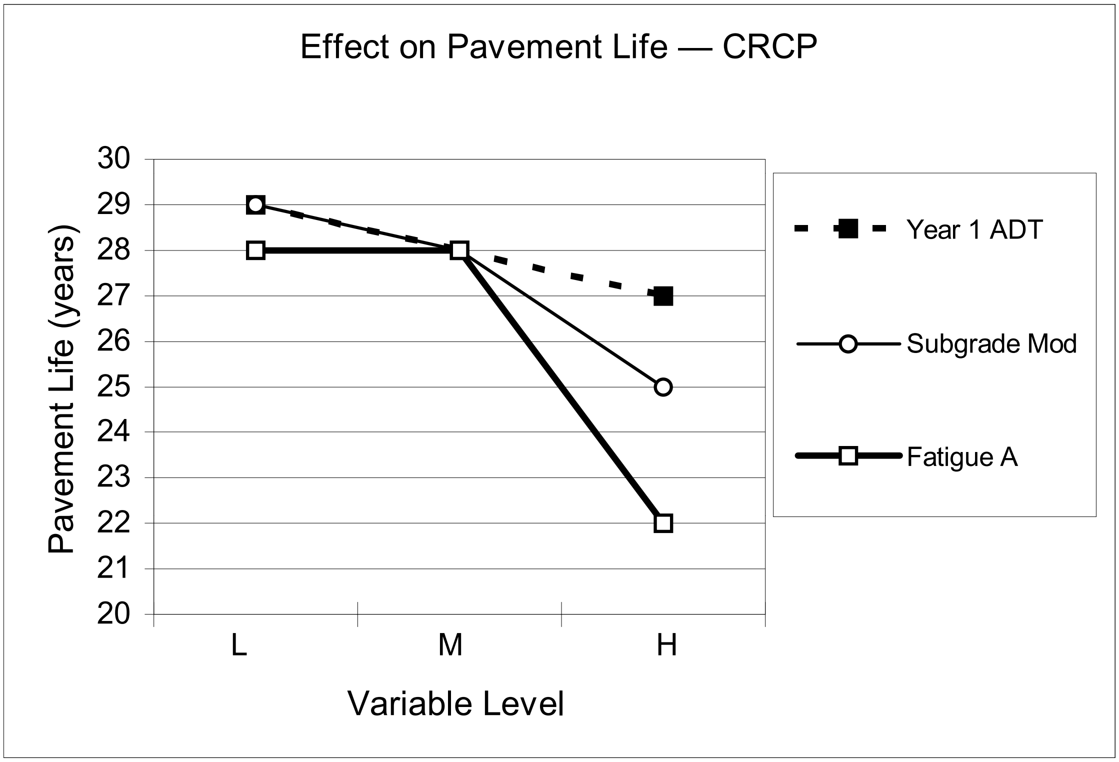

Figure 5.7. Effect of Year1ADT, SubgradeMod, and FatigueA on Life — CRCP

Figure 5.8 is a plot of five other variables that also have a "Very High" sensitivity rating. But these five variables are so sensitive that the pavement alternative failed before reaching two-thirds of its design life. Thus the life-cycle cost and delay cost results are not significant. Figure 5.8 is the only plot that shows the effect of these five variables on CRCP alternatives.

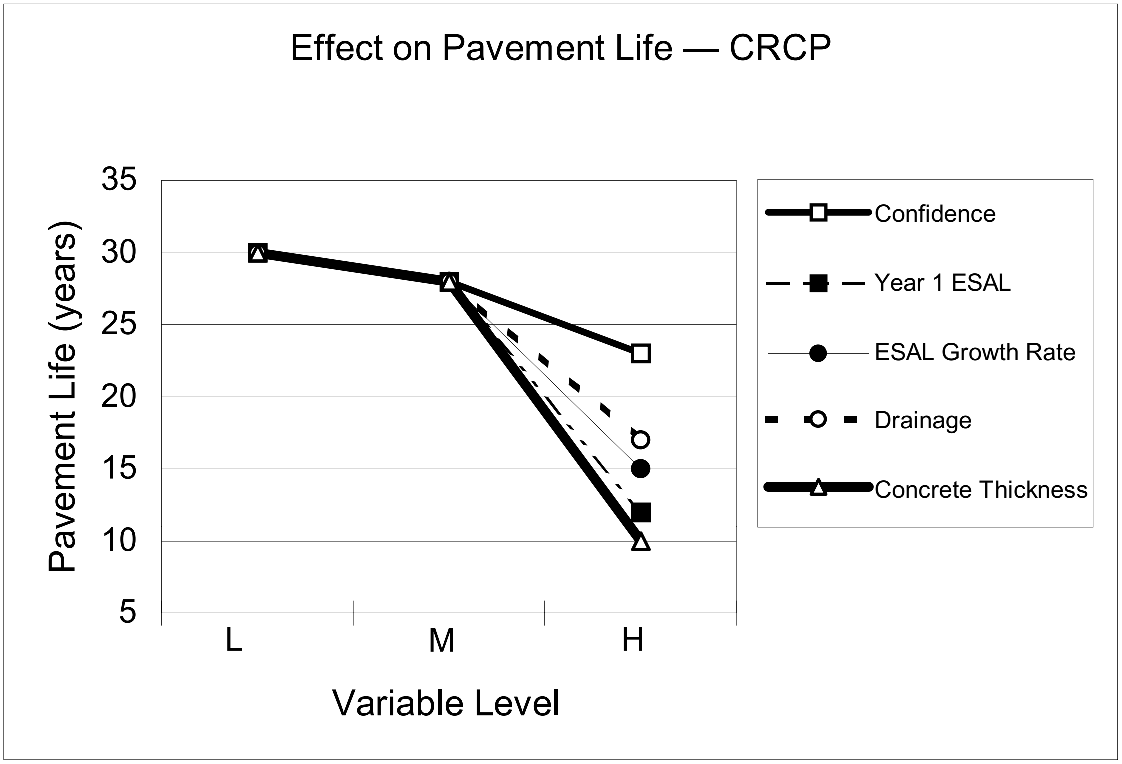

Figure 5.8. Effect of five "Very High" Variables on Pavement Life — CRCP

CHAPTER 6. DISCUSSION OF RESULTS

The results obtained from the sensitivity analysis have implications on chiefly two areas. Users can use the data and sensitivity ratings as a knowledge base to help them run the program efficiently, and the results can be used to decide what models need to be changed or altered in future revisions of the program.

6.1 IMPLICATION OF FINDINGS

This sensitivity analysis will be extremely helpful in assisting the user by giving him or her a valuable range of inputs and known outputs, as well as by identifying variables that can be altered slightly to obtain a desired outcome.

Computer programs are never static — they are constantly in a state of revision, whether the user knows it or not. The results of this sensitivity analysis can be used to improve the program in the future by giving the computer programmer a database of information to work from. Certain variables, such as those rated with a "Very High" sensitivity, can be reduced in magnitude if it is deemed necessary. Conversely, some of those variables with no sensitivity (rated "None") should perhaps be changed to have some effect on the life-cycle cost calculations. In addition, the "Opposite" rated variables should also be examined more carefully to determine if this result was simply a combination of "strange" inputs or a bug in the computer code somewhere.

6.1.1 Critical Inputs

Critical inputs are those input variables that have the biggest effect on life-cycle cost or pavement performance. In this sensitivity analysis, the most critical inputs (shown in Table 6.1) were found to be those that had the "Very High" sensitivity rating.

Table 6.1 Critical Inputs

"Very High" Sensitivity Variables	**Description**
Confidence	Overall Level of Confidence
Year1ESAL	First-Year Equivalent Single-Axle Loads
ESALGrowthRate	ESAL Growth Rate
AnalysisPeriod	Analysis Period
Year1ADT	First-Year Average Daily Traffic (for pavement loading calcs.)
PSILimit	Present Serviceability Index Lower Limit
Drainage	Drainage of Pavement Structure (excellent to very poor)
L1Thick	Thickness of Concrete (Layer 1 in pavement structure)
SubgradeMod	Modulus of Subgrade Reaction
FlexStrength	Flexural Strength of Concrete
TiedEdge	Tied Concrete Shoulder? (Yes/No)
FatigA	Fatigue Parameter A

6.1.2 Applications

The Rigid Pavement Life-Cycle Cost Analysis (RPLCCA) program was created and designed for the Texas Department of Transportation (TxDOT), and the nature of the program reflects as much. Many of the features of the program are suited to the way TxDOT operates. For example, the equivalent single-axle load (ESAL) calculations can be done in one of two ways, one of which is the standard TxDOT method.

The program is most likely to be used by engineers working for state departments of transportation, county maintenance and construction divisions, and cities or municipalities. The RPLCCA program is set up to be used in many situations. Currently, only JRCP and CRCP types can be used, but the modular nature of the program ensures that other pavement types (and their associated performance calculations, modules, etc.) can be accommodated in the future.

Different traffic control strategies can be used on similar pavement designs to determine which is more efficient; JRCP designs can be compared to CRCP designs;

and life-cycle costs between different pavement thickness can be compared, just to name a few strategies.

6.2 LIMITATIONS

The RPLCCA program has some limitations, which may restrict its applicability and usage. But the facts that this program is the first of its kind and that this is a first version make the limitations seem less significant. The first limitation is that the user does not know how much money is spent on maintenance costs each year, or even in total, over the analysis period. The program does calculate it, but it should also specify the maintenance and rehabilitation costs over the life of the project. This lack of information may lead the uninformed user to make decisions based on faulty assumptions or incorrect data input.

6.2.1 Capabilities

The program is extremely useful in that it combines many programs into one. There are the performance module, the overlay strategy selection module, the cost calculation equations, and the financial equations, which bring all costs down to the present value.

6.2.2 Confidence Levels

The RPLCCA program has, as one of its inputs, a confidence level for the whole project (with any number of alternatives). This is one of the critical inputs, as mentioned in Table 6.1. This input variable has a huge effect on the performance of the pavement alternative, regardless of type. This is because a higher confidence level, 0.95 for example, means that the pavement has a 95% chance of lasting at least as long as the program calculates. But this is not a good assumption. There are so many factors involved in constructing a concrete pavement, much more than the 138 input variables in this program, that assuming a confidence level of over 90% is foolish. When the pavement is constructed, an engineer might be 50–75% sure that it is going to last as long as he or she designed it for. But construction variables, such as air temperature and evaporation, play a very important part. The RPLCCA program does try and take these into account, but a person cannot predict the future. That is to say, what an engineer designs for may not happen.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

As life-cycle cost analysis becomes more important and essential to all aspects of highway planning and pavement design, the Rigid Pavement Life-Cycle Cost Analysis (RPLCCA) program will become a more useful tool. But all tools need to be cared for, and this sensitivity analysis is the first step in "sharpening" this tool. This report presented the design, inputs, and results of the sensitivity analysis performed on the RPLCCA program, recommendations for improvements to be made to the program, as well as further research activities to be performed.

7.1 SUMMARY

Life-cycle cost is the only effective, cost-based method of comparing different construction alternatives at the same level. The framework for life-cycle cost calculations built into the RPLCCA program considers as many aspects of a project's different costs as possible, making it the most comprehensive life-cycle cost program of its kind today. This comprehensive quality makes the program subject to varying degrees of sensitivity within the whole of the input variables. That is why a sensitivity analysis is essential to this program's development.

The sensitivity analysis performed on the RPLCCA program included decisions regarding the ranges and values to be used for each of the input variables, running the program repeatedly, changing the input variables one at a time to the low and high values, and analyzing the results of the sensitivity analysis to determine critical inputs and recommendations for improvements.

7.2 CONCLUSIONS

The RPLCCA program is a one-of-a-kind, extensive, and thorough computer program that is extremely useful in making decisions regarding concrete pavement projects. There are many input variables to the program that require some knowledge of how the program works before they are fully understood. These inputs are those that will most affect the outcome of the program. The sensitivity analysis discussed in this report identified those input variables and quantified their effect.

Users of the RPLCCA program, as well as computer programmers who are tasked with revising it, can use this publication to their advantage. This report will allow users to better understand how the program functions, allowing them to expand its applicability and obtain results that they can be confident with.

7.3 RECOMMENDATIONS

This study presented the basic concept behind the RPLCCA program used for performing life-cycle cost analyses. Included in the RPLCCA framework are models that predict pavement performance, user costs and accident rates at work zones, and possible rehabilitation designs. Many of these models are outdated and should be replaced by more reliable models, as well as be calibrated to specific local conditions. This is especially applicable to the pavement performance models. Research should be undertaken to replace these models and to improve the predictive quality of the framework. The models currently included in the computer software can be replaced without much difficulty.

In addition to replacing the existing models that are out of date and poor predictors of pavement performance, new models should be developed that can predict the effects of increased air pollution, business impacts, noise, overlays, and other components that may be identified in future research.

A major improvement that should be undertaken is the ability to automatically calibrate the performance models using local condition survey data. This could be accomplished by allowing the engineer to enter distress information along with historical, environmental, and as-built construction data. In addition to this information, variability in such construction aspects as concrete strength, slab thickness, and surface roughness should be used to calibrate the models. Once a methodology is developed, this functionality can be integrated into the RPLCCA software and an additional sensitivity analysis on the new program can be initiated with the recommendation that all outputs of the program be recorded.

Also, specific problems with the Visual Basic/Visual Fortran code and the graphical user interface of the RPLCCA program include the following:

- The program should spell out what maintenance activities were performed over the life of the pavement alternative, as well as over what percentage of the project the activity was performed.
- The option of having the program *choose* an overlay for the pavement (if one is required) should be added, so that the program can eliminate the need for user intervention in selecting an appropriate overlay option.
- Equations that calculate the performance of overlays should be added. As it stands now, the program assumes that the present serviceability index (PSI) of the pavement structure remains constant after the overlay has been added.
- The *Loading* tab in the General (or Project) Inputs screen needs to be improved; currently, the program defaults to one method of calculating equivalent single-axle loads (ESALs). This method needs to be verified to make sure it works correctly; at that point the other method can be corrected and implemented.
- There is a problem with the *Delay* tab in the General Inputs screen; the Diversion Criteria (Length or Time) does not stay on what is selected. When the window is reopened, the length option is always highlighted.

REFERENCES

1. Wilde, W. James, *Life Cycle Cost Analysis of Portland Cement Concrete Pavements.* Doctoral Dissertation, The University of Texas at Austin, December 1998.

2. American Association of State Highway and Transportation Officials, *Road User Benefit Analyses for Highway Improvements,* Washington, D.C., 1952, Revised 1960.

3. Intermodal Surface Transportation Efficiency Act, 1991.

4. Transportation Equity Act for the 21st Century, 1998.

5. Mrawira, Donath, William J. Welch, Matthias Schonlau, and Ralph Haas, "Sensitivity Analysis of Computer Models: World Bank HDM-III Model," *Journal of Transportation Engineering,* September/October 1999.

Appendix A. System Requirements for Installing the RPLCCA Program

RIGID PAVEMENT LIFE CYCLE COST ANALYSIS PROGRAM

(RPLCCA v1.0)

System Requirements

<u>CENTER FOR TRANSPORTATION RESEARCH</u>
The University of Texas at Austin
3208 Red River, Suite 200
Austin, Texas 78705-2605
472-8875 — FAX 480-0235

SYSTEM REQUIREMENTS

The Rigid Pavement Life-Cycle Cost Analysis program has the following hardware/software requirements:

- personal computer with a Pentium or higher processor
- Microsoft Windows 95 or higher operating system (Windows NT not supported yet)
- 8 MB of memory
- 20 MB of available hard disk space
- CD-ROM drive (setup program also available on zip and floppy disks)
- VGA or higher-resolution video adapter
- mouse or other compatible pointing device

Appendix B. RPLCCA Installation Guide and User's Manual

RIGID PAVEMENT LIFE CYCLE COST ANALYSIS PROGRAM

(RPLCCA v1.0)

Installation Guide / User's Manual

CENTER FOR TRANSPORTATION RESEARCH
The University of Texas at Austin
3208 Red River, Suite 200
Austin, Texas 78705-2605
472-8875 — FAX 480-0235

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SECTION 1. INSTALLING THE PROGRAM

Before starting the installation program, close down any programs that are running to avoid loss of data or errors in the setup program. Insert the disk or CD provided with the software package, and double-click on the *setup.exe* file located on the CD or disk. Follow the instructions that come up on the screen, making sure to accept any default file paths that the setup program suggests.

If the setup program requires that you restart your computer, click the *OK* button. In this case, you will have to re-run the setup program (once the computer has restarted) by double-clicking on the *setup.exe* file again as before. Once the setup program is completed, a message should come up stating that the installation was successful. Click the *OK* button, and you are now ready to use the RPLCCA program.

SECTION 2. STARTING THE PROGRAM

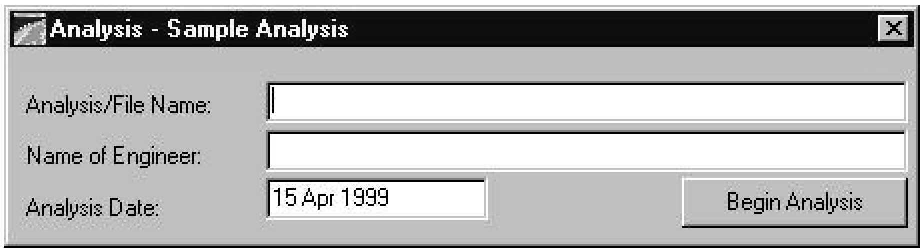
Press the *Start* button on the taskbar, go to *Programs -> Rplcca1*, and then to *Rplcca1*. The program should then start loading up. The screen that appears will look like this:

Illustration 1. Main RPLCCA screen

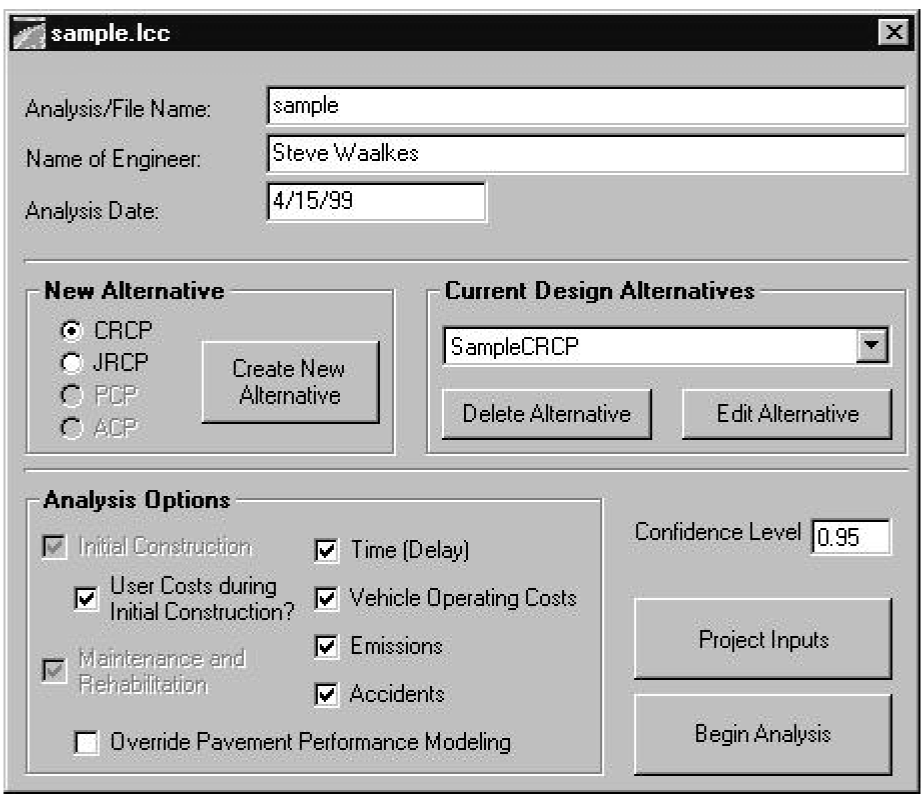
To open the example file that comes with the software package, go to *Analysis -> Open*, or press the  button, or press *CTRL-O*. The name of the file is *Example Problem.lcc*, and it can be opened by double-clicking on it or by selecting it once and pressing the *Open* button.

SECTION 3. CREATING A NEW FILE

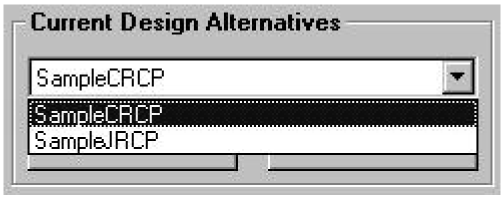
To start a new file, go to *Analysis* -> *New*, or press the button, or press *CTRL-N*. The following window will then open:



Enter the desired filename for the file, without any filepath or extension, as well as your name. You may use either the <TAB> key or the mouse to move between fields. Press the *Begin Analysis* button when finished with this initial step. Once you have done this, the following window will come up:



This is the main analysis window. If you click on the pull-down menu under *Current Design Alternatives*, you will notice that there are two default alternatives supplied with every new file created, one named *SampleCRCP*, and the other *SampleJRCP:*



To add a new alternative to the existing ones, first select the type of alternative you want to add, a Continuously Reinforced Concrete Pavement (CRCP) or Jointed Reinforced Concrete Pavement (JRCP) alternative;

and press the *Create New Alternative* button:

A dialog box will pop up asking you to choose a template from which to base the new alternative:

You may choose to use either RPLCCA Default Values, which are the same as the values in the SampleCRCP or SampleJRCP alternatives (from the new file you just created), or you may choose to base the new alternative on the selected existing alternative (highlighted in the

Current Design Alternatives box). The last option is to use output files from a Center for Transportation Research (CTR) program, such as CRCP8 or JRCP6. For more details on this option, consult the sensitivity analysis of this publication.

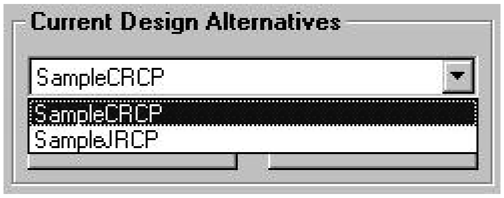
To delete one of the alternatives, just select the one you want to delete in the pull-down menu under *Current Design Alternatives* and press the *Delete Alternative* button:

SECTION 4. PROGRAM INPUTS

The RPLCCA program is split up into two data entry parts: the first is the alternative-specific data entry mode, and the second is the project data entry mode. Characteristics such as steel reinforcement and concrete properties are specific to each alternative, so they are accessed by pressing the *Edit Alternative* button (with the desired alternative highlighted). A particular pavement project will also have certain characteristics that are the same, regardless of what type of pavement is constructed, so such things as loading characteristics, project geometry, and economic factors are all grouped under the *Project Inputs* portion of the data entry.

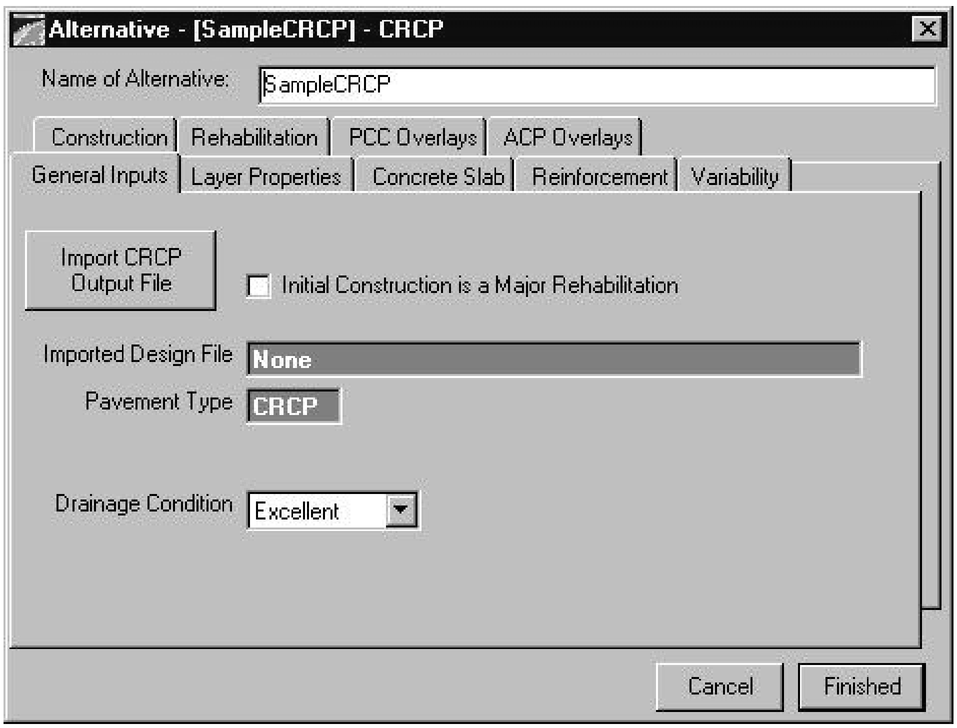
Section 4.a Alternative-Specific Inputs

After selecting the desired alternative to edit;



press the *Edit Alternative* button:

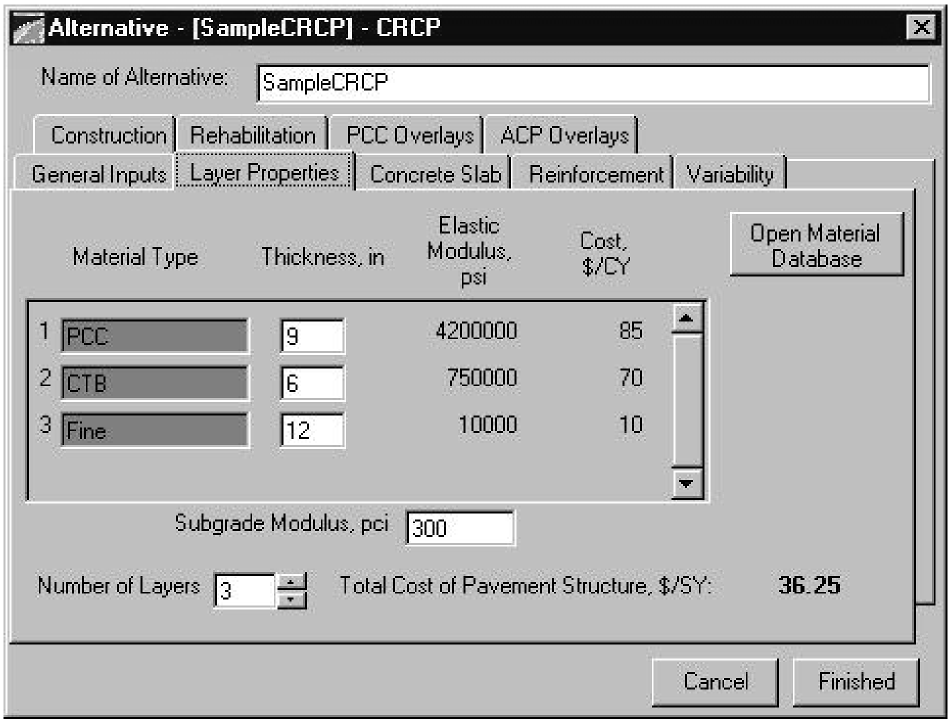
A window will pop up that looks like this:



This is the *General Inputs* tab of the alternative, which displays basic information about the design alternative. Here again is the option to import an output file from a CTR program such as CRCP8 or JRCP6, and if this option is selected, the file path for the output file will appear in the *Imported Design File* box. At the top, the check box can be selected if the *Initial Construction is a Major Rehabilitation*, such as an overlay. The *Pavement Type* box shows the pavement type of the alternative, which cannot be changed, unless a new alternative is created. The pull down box for *Drainage Condition* can be varied from

Excellent all the way to *Very Poor*. At the very top of the window, the name of the alternative can be changed in this screen as in all the other screens for this design alternative.

The next tab is the *Layer Properties* tab:

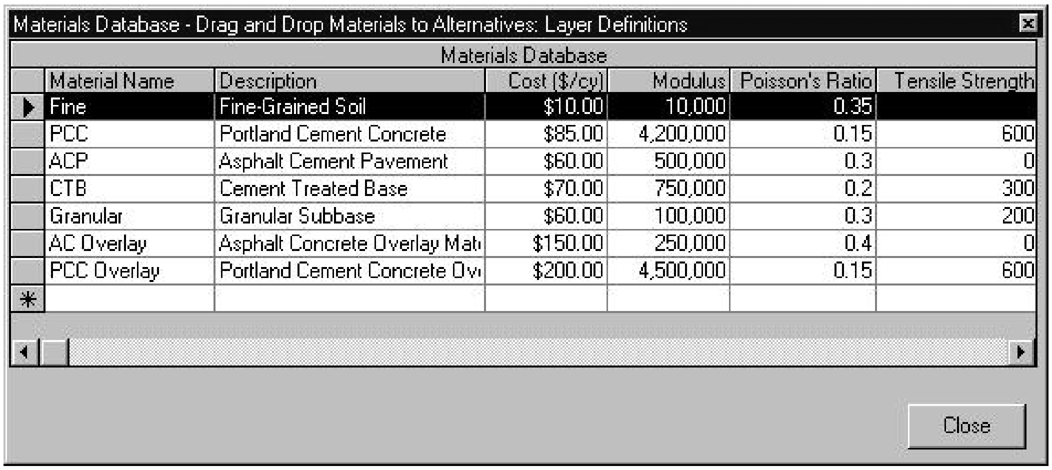


This tab helps define the layered structure of the pavement alternative. One tool to assist the engineer in designing the structure of the proposed pavement is the Material Database. A default Material Database is included with the Example Problem, which can be added to and customized to fit the user or agency's needs.

Each input file for the RPLCCA Program has its own Material Database, so if costs for materials change over time, they will have to be changed for each input file. This process can be expedited by opening the input file (the file with the .lcc extension) in Microsoft Access and importing the updated table from another lcc input file. Each input file is really a Microsoft Access database file, and each of the input values can be changed within MS Access.

To open/view/edit the Material Database, double-click on one of the layers in the pavement structure or press the *Open Material Database* button:

A window will pop up that looks like this:

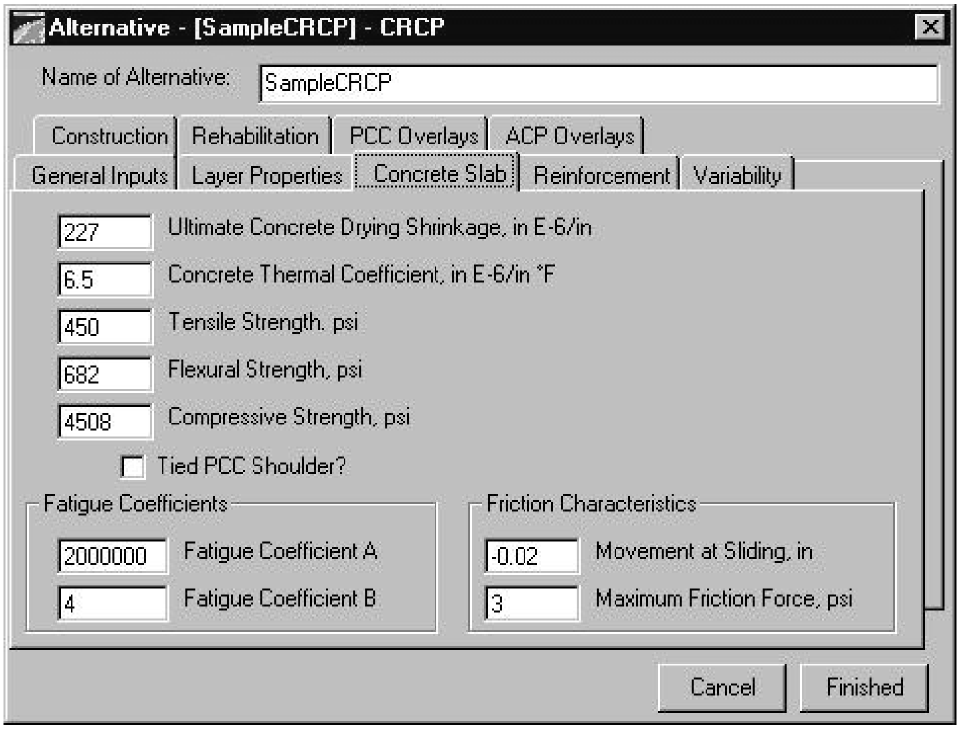


Material Name	Description	Cost ($/cy)	Modulus	Poisson's Ratio	Tensile Strength
Fine	Fine-Grained Soil	$10.00	10,000	0.35	
PCC	Portland Cement Concrete	$85.00	4,200,000	0.15	600
ACP	Asphalt Cement Pavement	$60.00	500,000	0.3	0
CTB	Cement Treated Base	$70.00	750,000	0.2	300
Granular	Granular Subbase	$60.00	100,000	0.3	200
AC Overlay	Asphalt Concrete Overlay Mat	$150.00	250,000	0.4	0
PCC Overlay	Portland Cement Concrete Ov	$200.00	4,500,000	0.15	600

Each of the materials/layers in this database can be changed simply by clicking on the field to be changed and typing a new value. New layer types can be added by typing them in the last line of the table. To add or replace one of the materials in the *pavement structure*, select the desired material in the database window and drag it into the desired position/layer in the alternative window, and drop it there. Click on the *Close* button when finished editing the database.

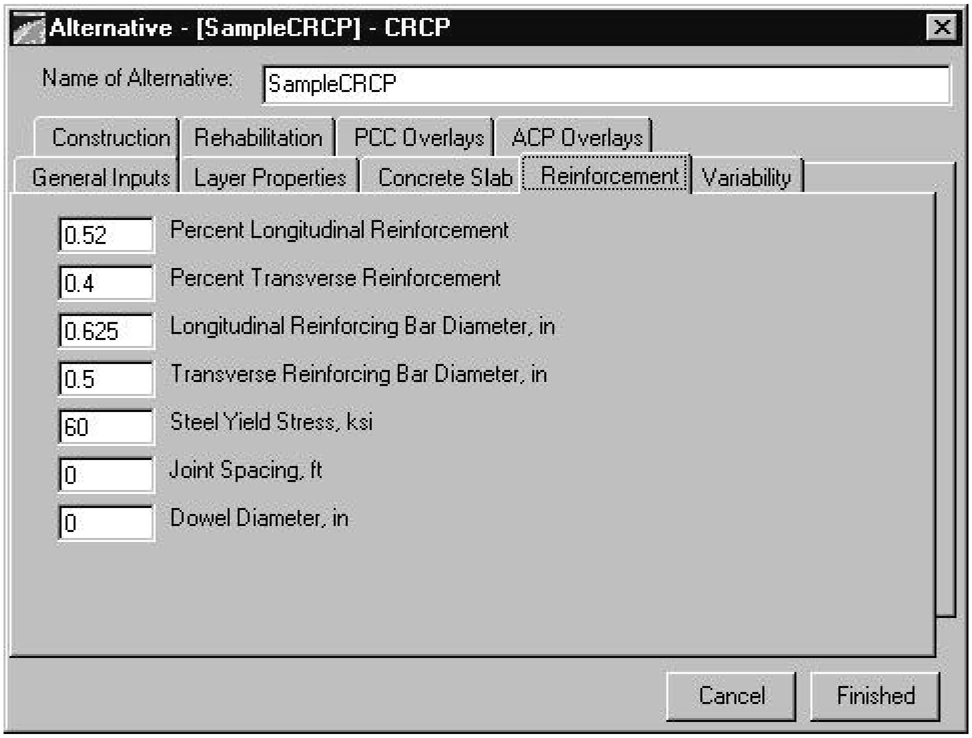
The subgrade modulus, in units of lb./in^3, as well as the number of layers in the pavement structure can both be changed in the *Layer Properties* tab of the *Alternatives* window. The program also computes the cost of the pavement structure, based on the costs per cubic yard from the materials database and the thickness of each layer.

The next tab is the *Concrete Slab*:



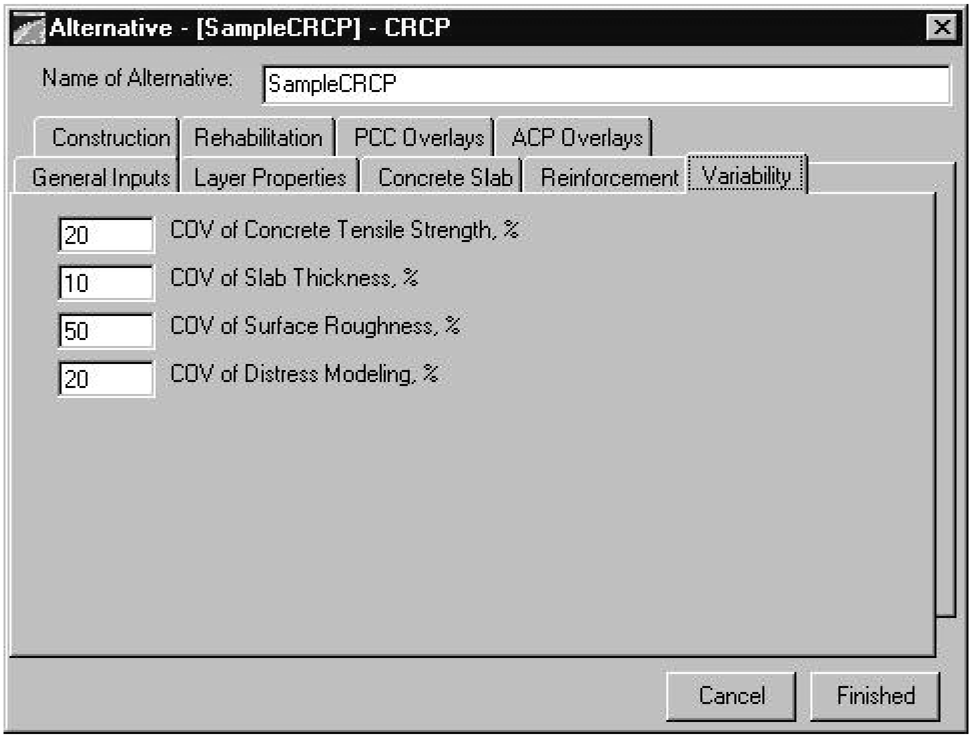
This tab is used for specifying the properties of the concrete after it has set or cured.

The next tab is the *Reinforcement* tab:



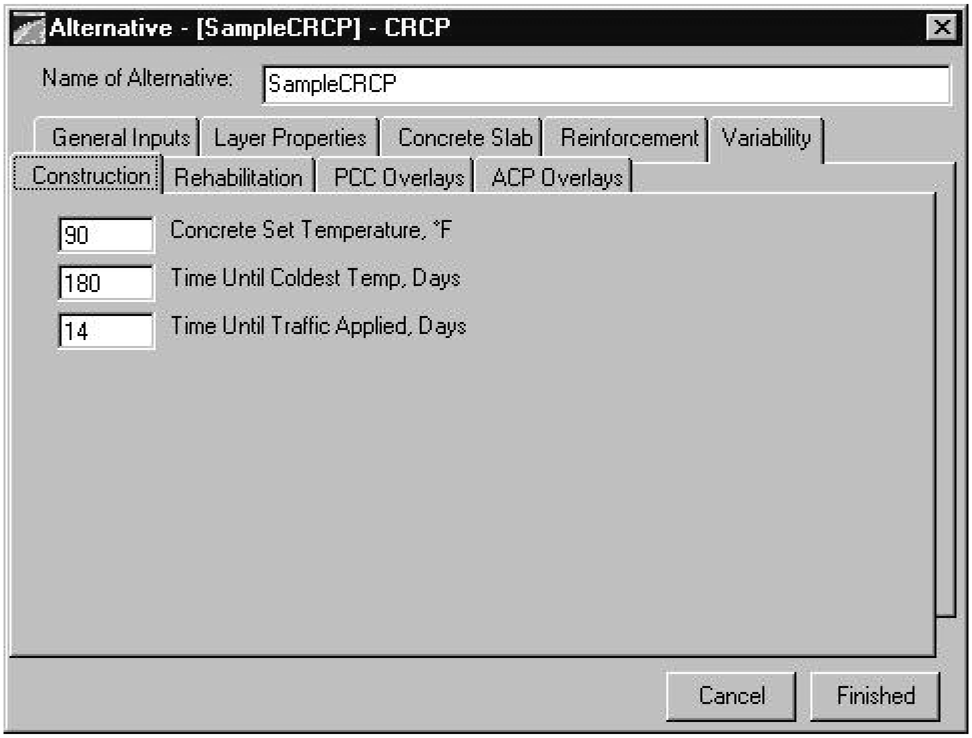
This screen is used to set the properties of the steel reinforcement used in the pavement structure.

The next tab is the *Variability* tab:



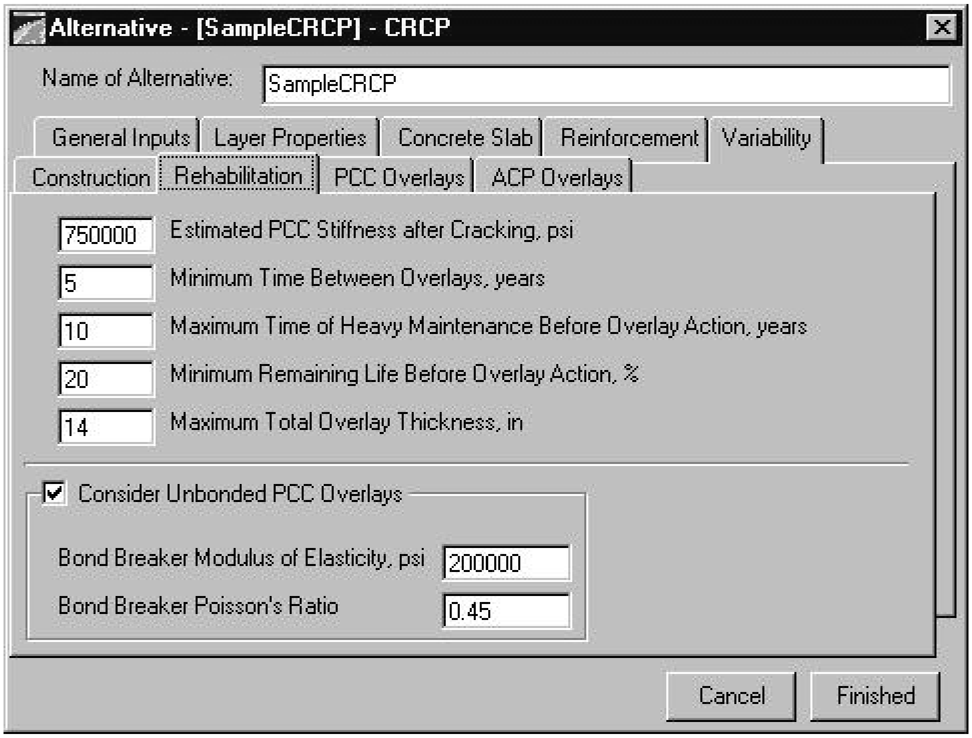
In this window, the coefficients of variance (COV's) for the various models used in the program are specified, since some of the models are based on statistical distributions.

The next tab is the *Construction* tab:



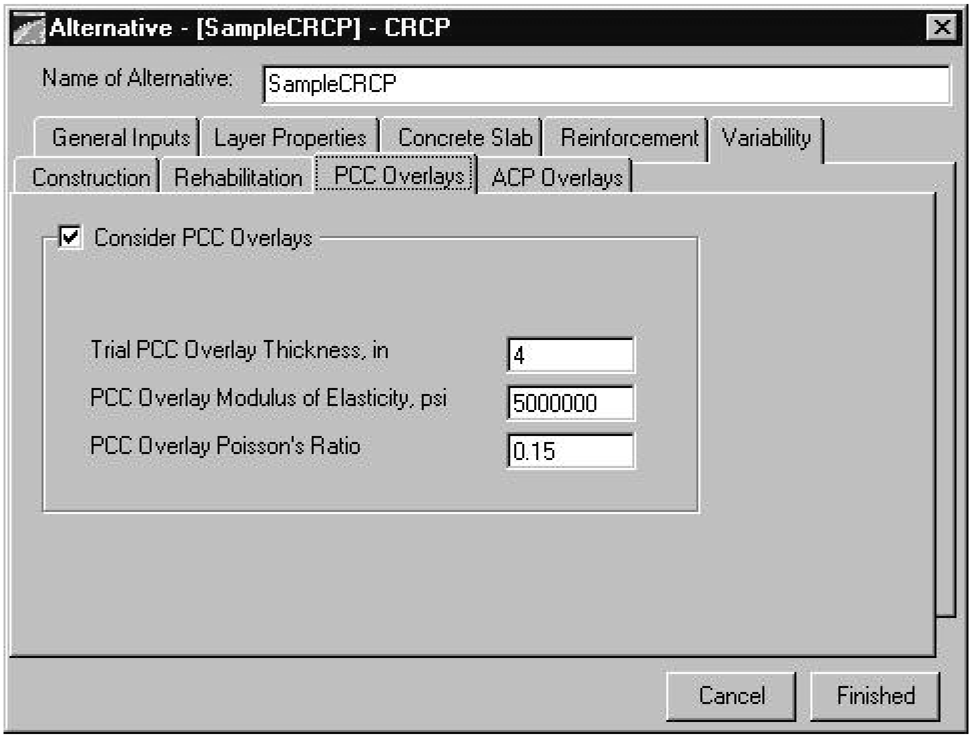
This window is used to set the various parameters related to the construction of the pavement, such as the concrete set temperature, and the times until traffic is returned to the roadway and the coldest temperature is reached.

The next input tab is the *Rehabilitation* tab:



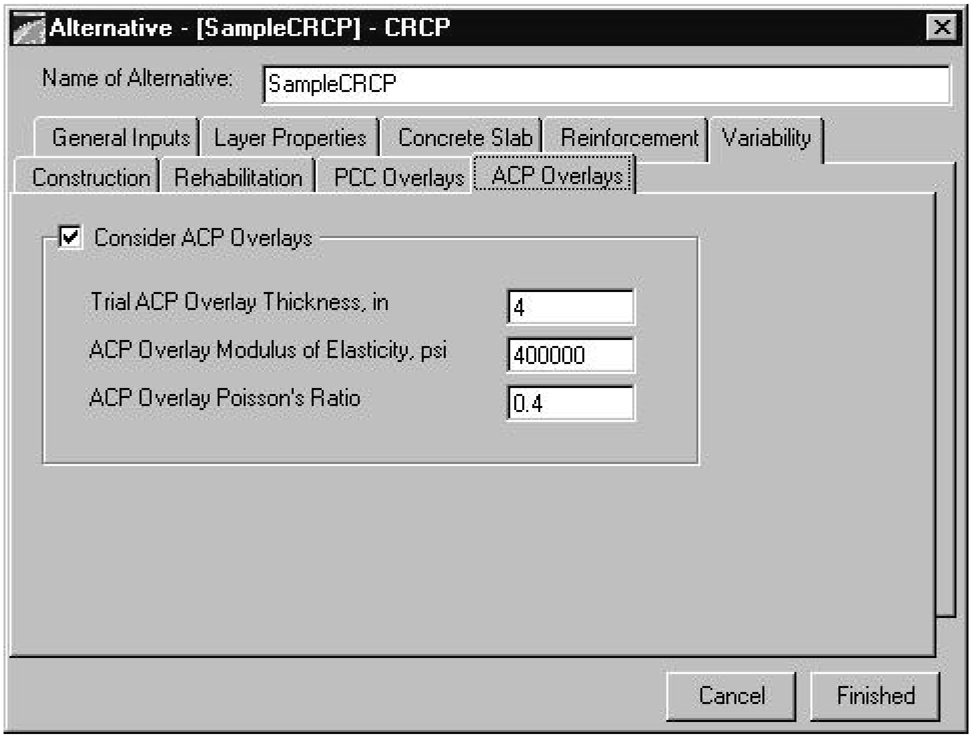
This window contains the input parameters related to the possible rehabilitation options available over the life of the pavement or period of analysis.

The next tab is the *PCC Overlays* tab:



The data for Portland Cement Concrete (PCC) overlays is required in this window, including trial thickness, modulus of elasticity, and Poisson's ratio.

The next tab is for *ACP Overlays*:



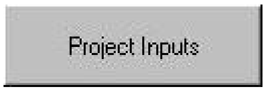
This window is similar to the PCC Overlays tab, except that these values are used for asphalt concrete pavement (ACP) overlay rehabilitation options.

Once all of the values for the alternative have been entered, press the Finished button:

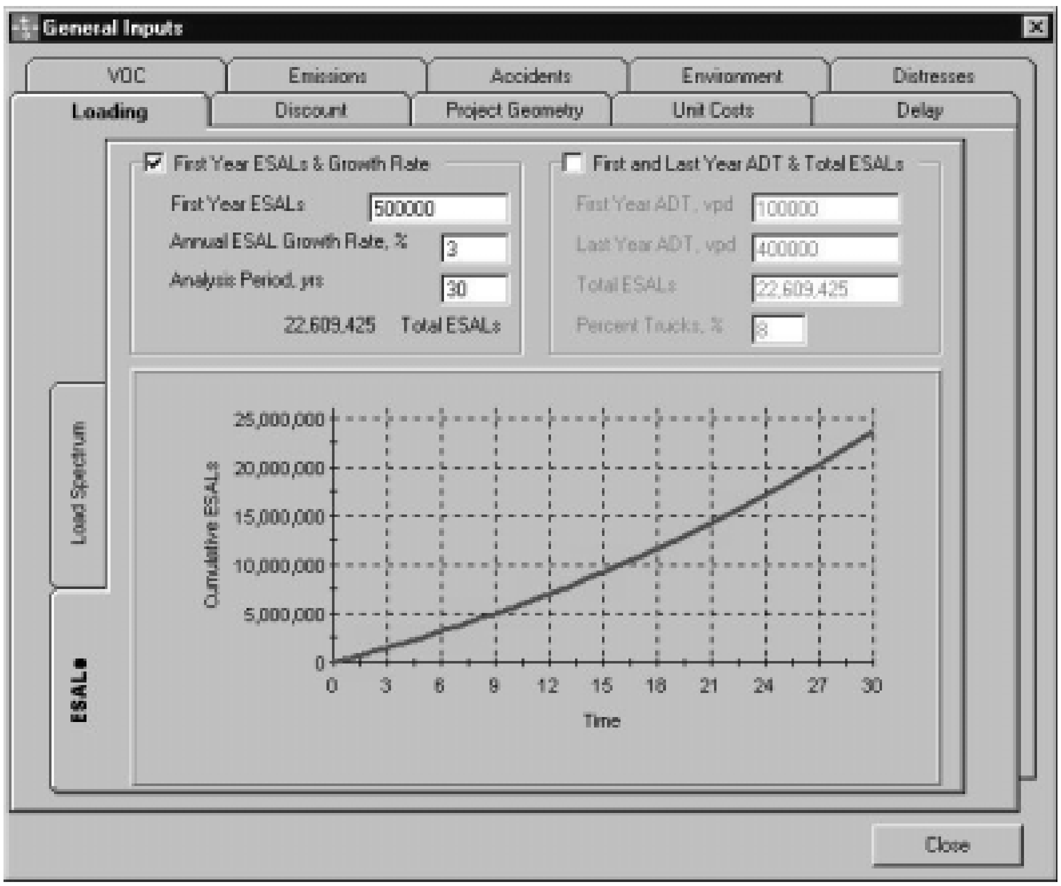
This will bring you back to main analysis window.

Section 4.b Project-Level Inputs

The next step is to enter the project-level inputs; the variables or characteristics that are consistent with different pavement alternatives. To start this data entry mode, press the *Project Inputs* button:

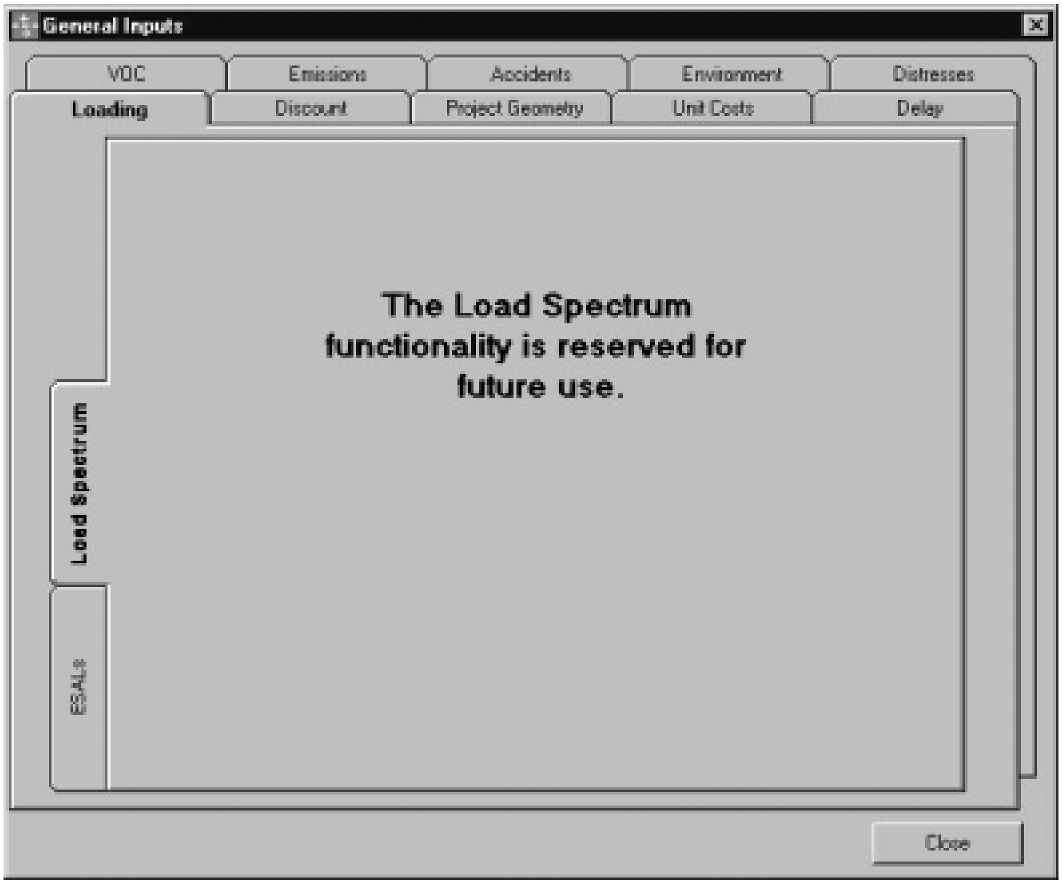


Pressing this button will bring up the following screen:



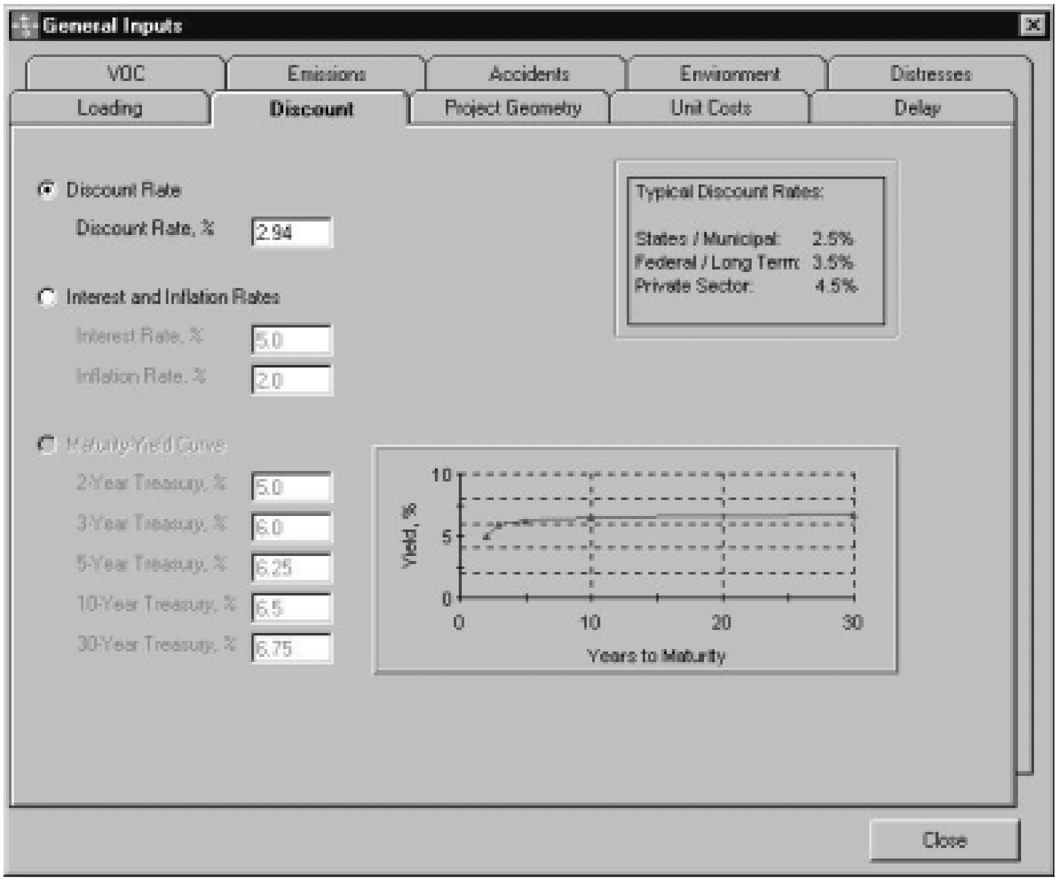
This tab is used to predict the loads expected to be applied to the pavement over the analysis period. There are two methods to do this, either by entering a first year ESAL (Equivalent Single Axle Load) number and a growth rate, or by entering first and last year ADT (Average Daily Traffic), total ESALs, and percent trucks. The plot shows a graphical representation of the cumulative ESALs over the analysis period.

The second sub-tab in the *Loading* tab is the *Load Spectrum* option, which is not currently enabled in this version:



In the future, it will be used to specify the number of load applications per axle weight range or category, which will take the place of using ESALs to estimate the loads applied to a particular pavement section. The load spectrum method is more accurate, since it calculates the stresses in the pavement due to each load, instead of converting to equivalent damage like the ESAL method.

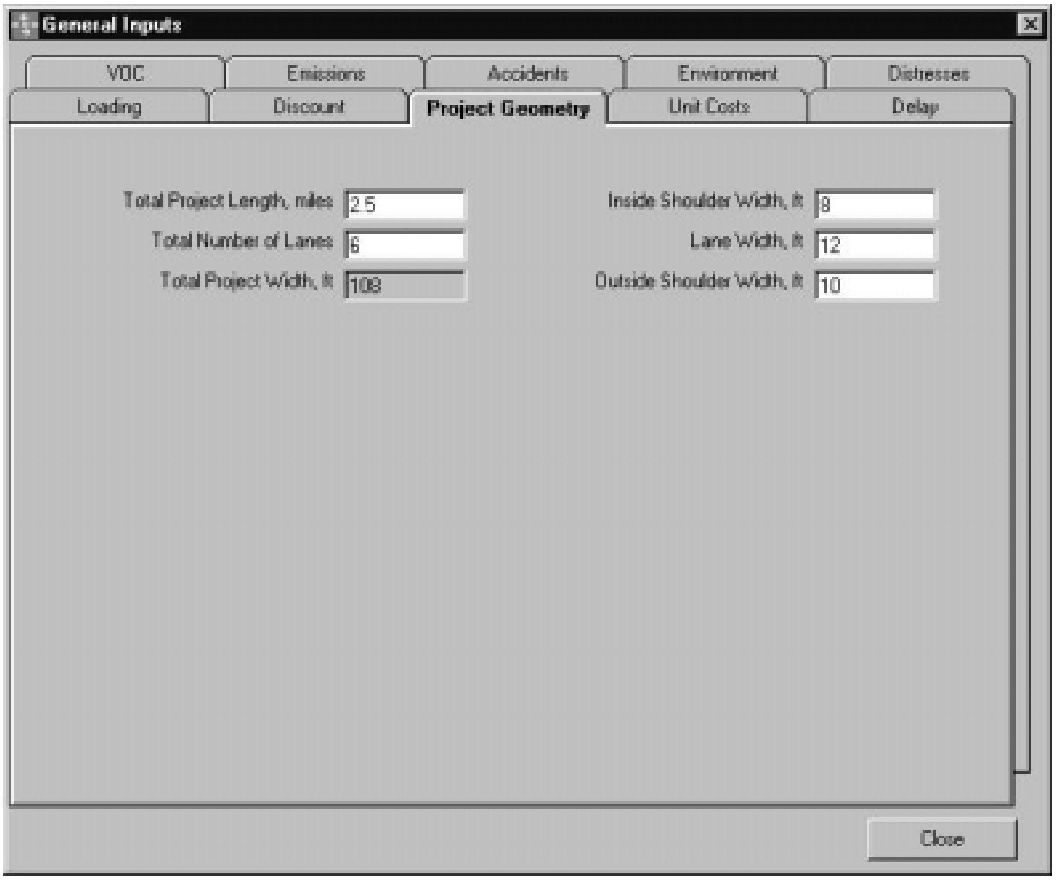
The next input screen is the *Discount* screen:



This screen is used to enter the financial/economic values that the user wishes to use for the economic analysis over the specified period. There are three options on the screen, but only two of these are functional in this version: discount rate and interest/inflation rates. There are suggested (typical) values for discount rates for the type of agency that is borrowing the funds and issuing the bonds for the project. The plot shows the yield over the life of the project.

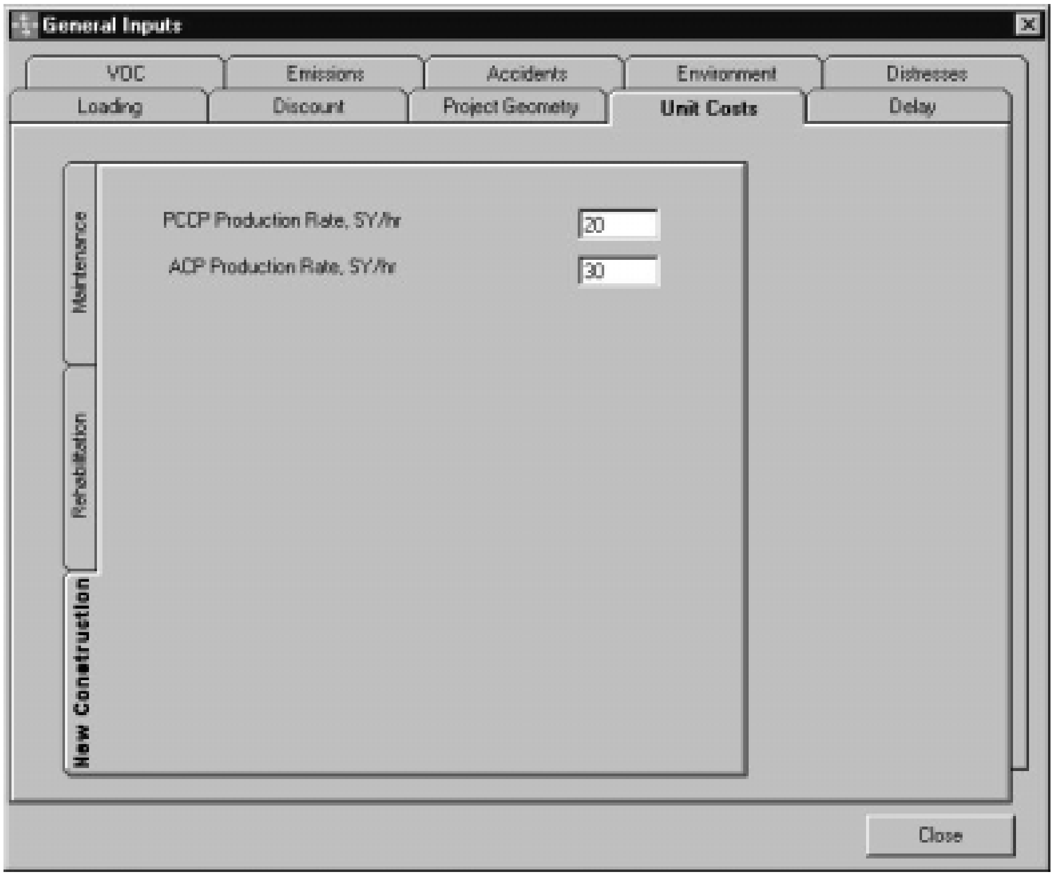
The option that is disabled in this version is the Maturity Yield Curve for Treasury Bonds and Treasury Bills. If the yields of T-Bonds and T-Bills are known, the program will calculate the interest over the life of the project.

The next tab in this input mode is for the *Project Geometry:*



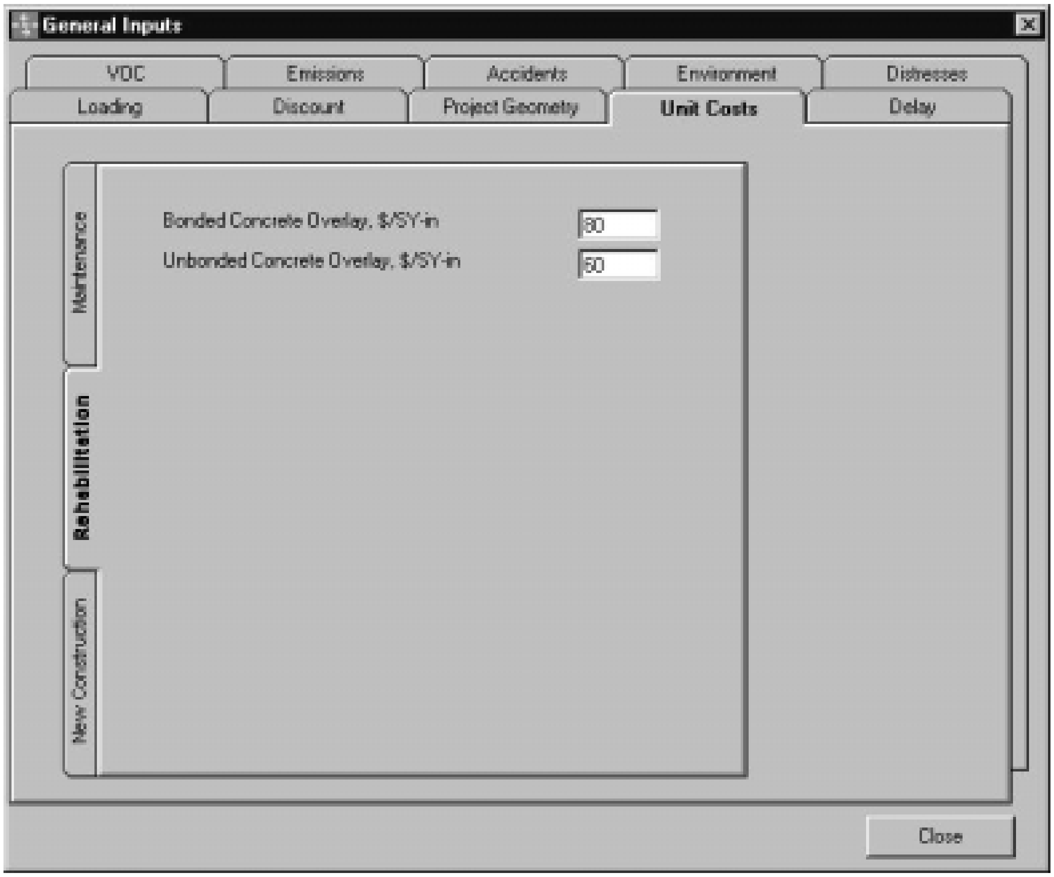
This portion of the input is used to specify the length and width of the project. The length of the project, number of lanes, and dimensions of the roadway are entered on this screen, and the total project width is calculated from those values.

The *Unit Costs* tab is next:



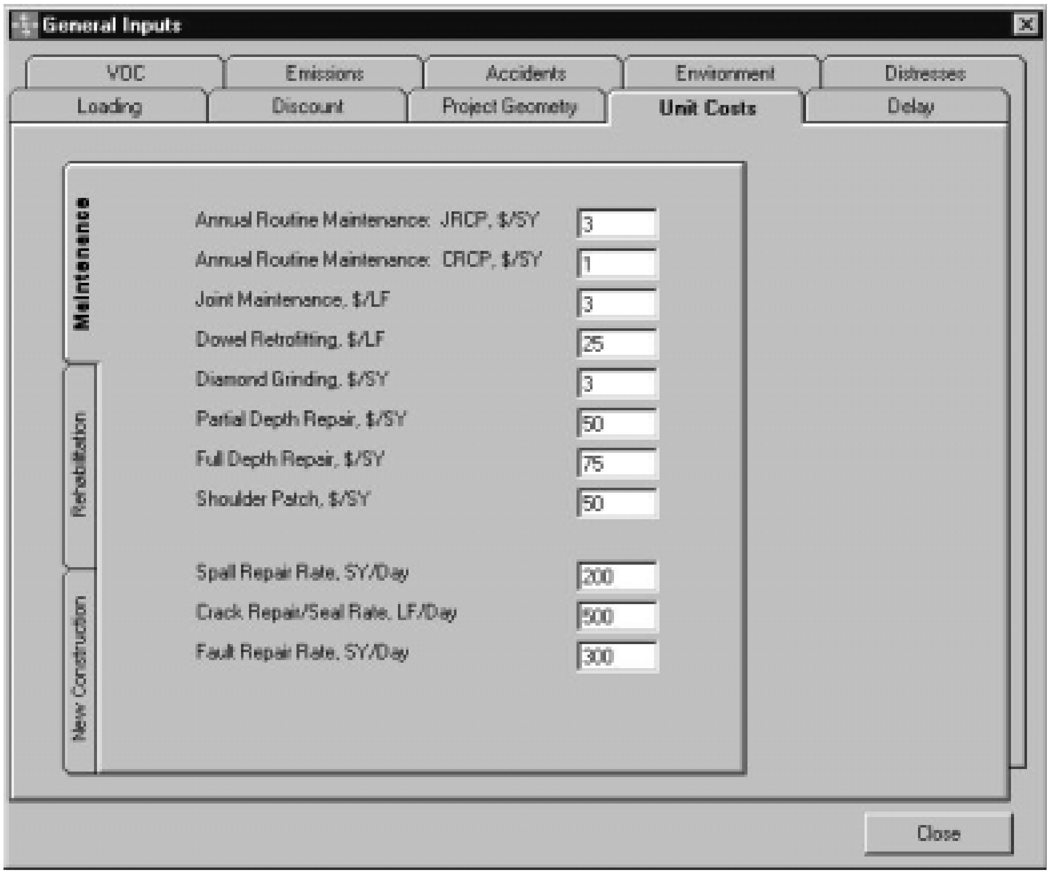
The first input screen that shows up is for *New Construction.* The values entered on this screen are production rates for both Portland Cement Concrete (PCC) and Asphalt Concrete (AC) pavements.

The next input screen under the *Unit Costs* tab is for *Rehabilitation:*



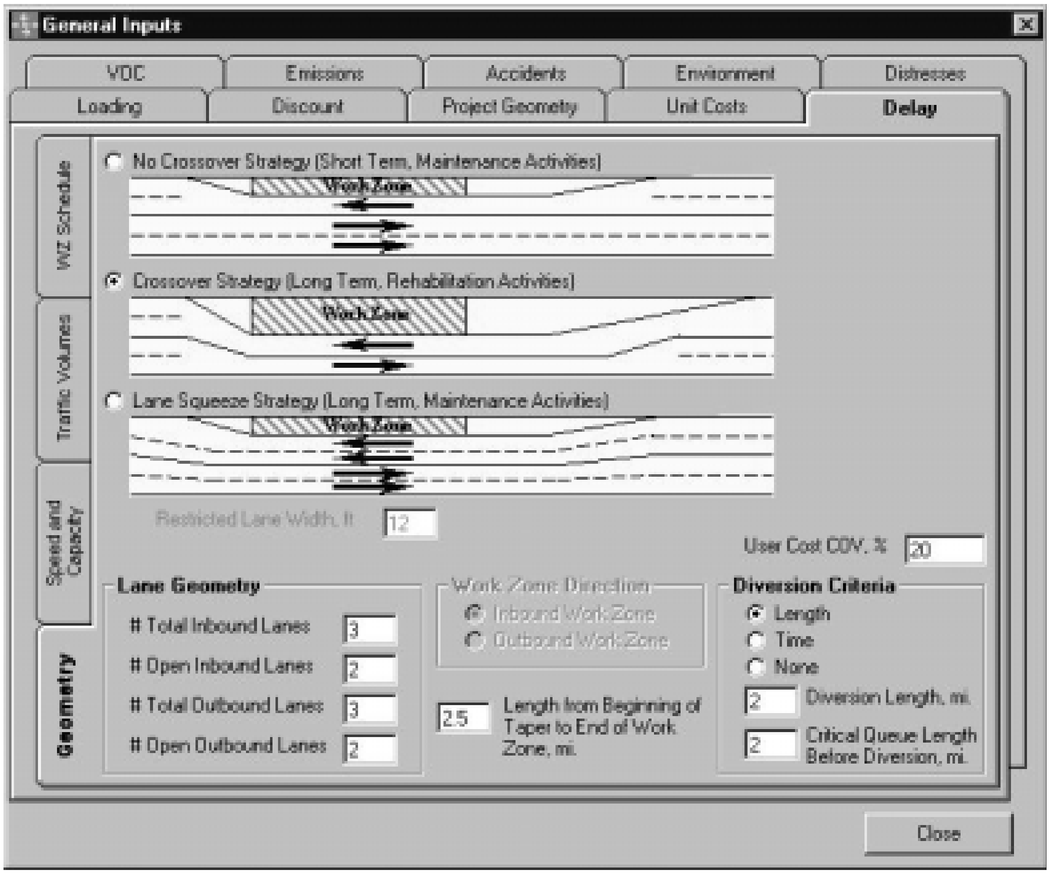
This part of the input is used for PCC overlay costs, both bonded and unbonded types.

The next tab is the *Maintenance* tab:



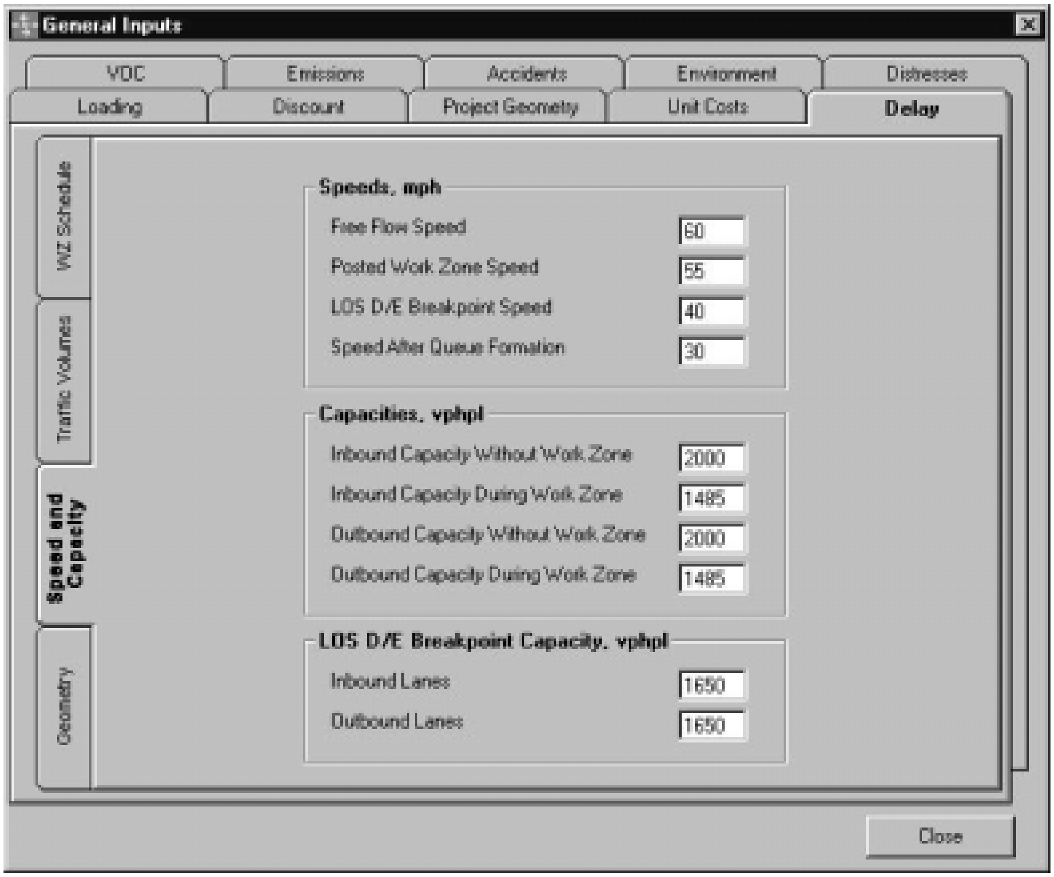
This input screen is used for costs and production rates of routine maintenance items.

The next tab in the General Inputs window is the *Delay* tab, which is used to calculate the delay time (and costs) associated with the construction project:



This portion (the *Geometry* tab) of the *Delay* input screen allows the user to define the traffic control strategy, narrow lane width (if applicable), number of open lanes, work zone direction (if applicable), work zone length, coefficient of variance (COV) for user cost, diversion (detour) length/time, and the critical queue length (or time) before vehicles begin to divert/detour.

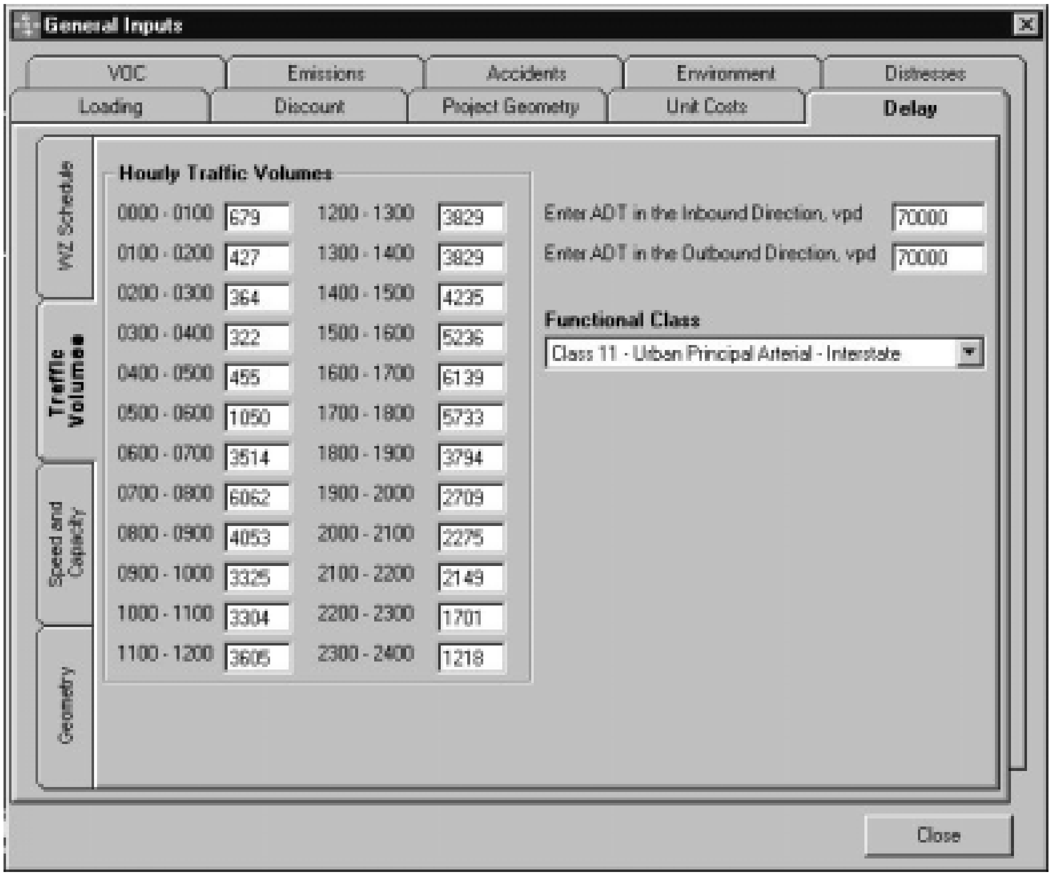
The next tab, *Speed and Capacity,* allows the user to input more traffic characteristics:



The first input box, Free Flow Speed, is the speed of vehicles without any delay or congestion (Level of Service A), and the second, Posted Work Zone Speed, is self-explanatory. The next input is the Level of Service D to E Breakpoint Speed: the speed at which the level of service of the facility goes from D to E. The last of the Speed inputs is the Speed after Queue Formation, which describes the speed of the vehicles in a queue at the work zone area.

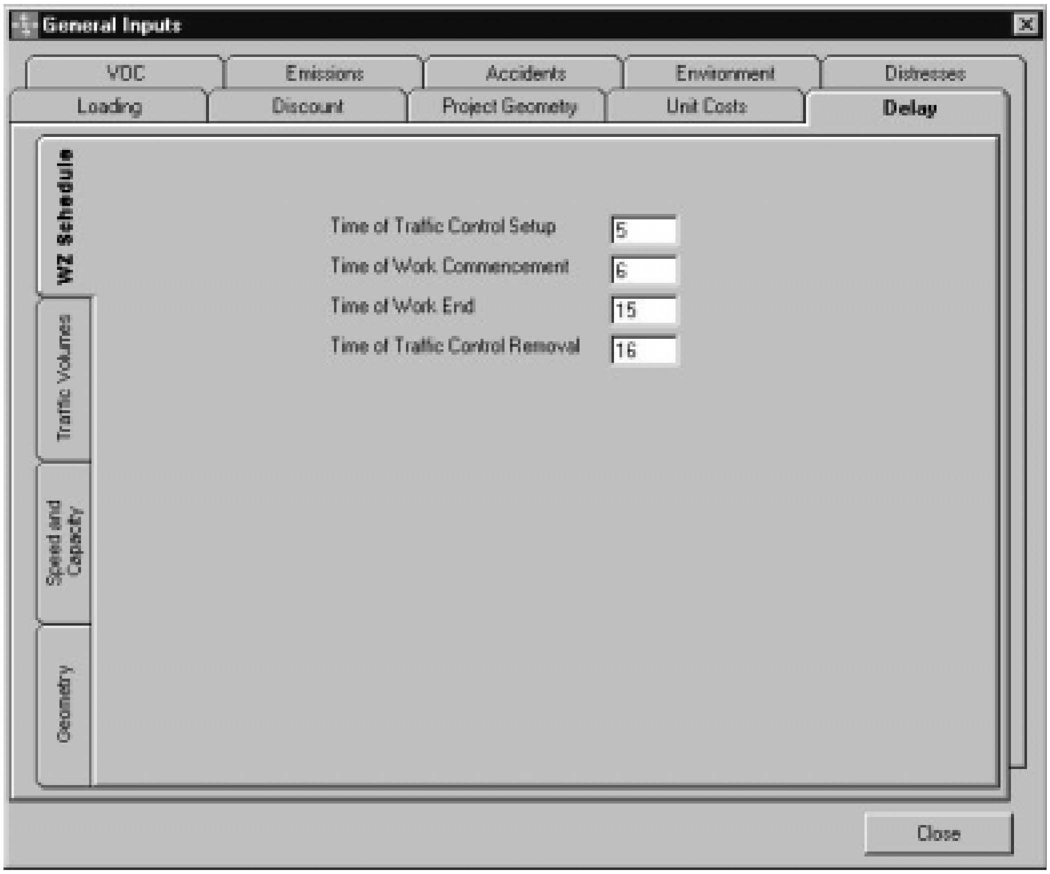
The capacities are split into *Inbound* and *Outbound,* and *Without Work Zone* and *With Work Zone,* but depending on the type of traffic control strategy selected, only one set (Inbound) will be active. The inbound and outbound capacities should be the same anyway, since this analysis program does not account for on- and off-ramps. The capacity at the breakpoint between level of service D and E is also required. This value can be calculated using Highway Capacity Manual (HCM) techniques.

The next input tab is the *Traffic Volumes* input tab:



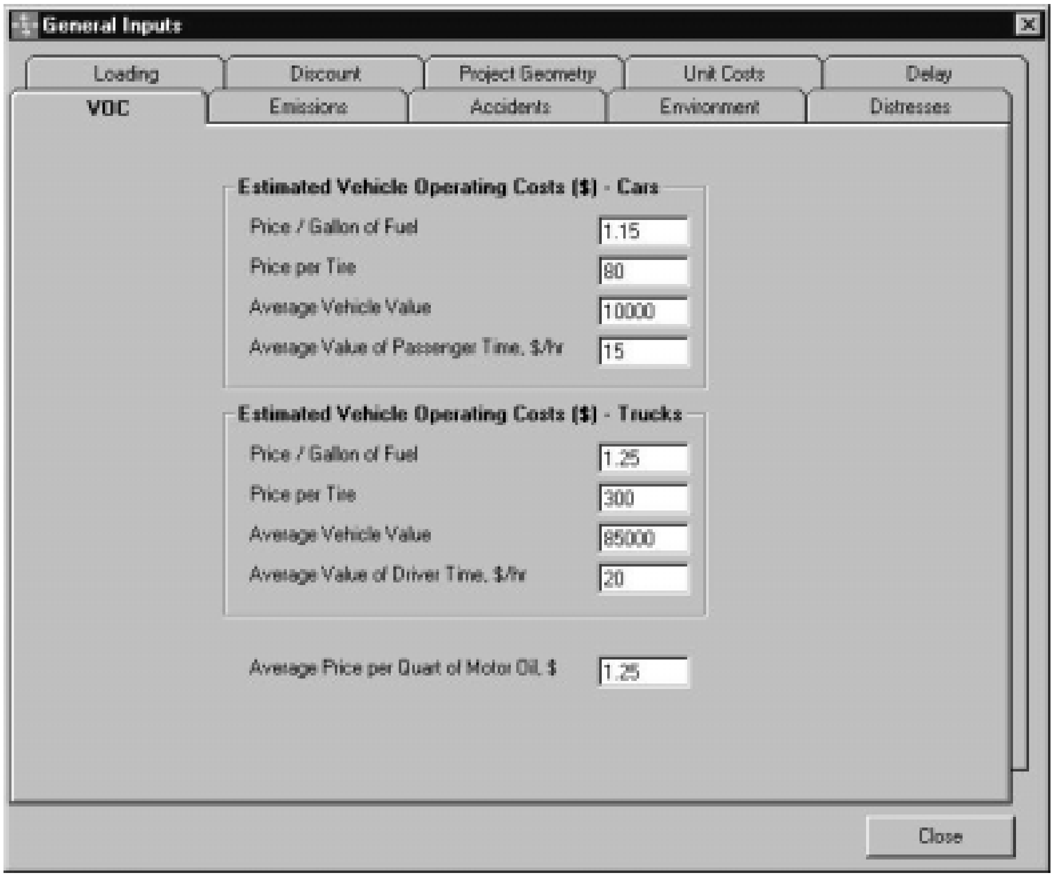
A choice must be made here when defining the traffic volumes to be used in the calculation of user costs; the first method is to input the hourly distribution directly, for each hour in the 24-hour period, and the other entails entering the ADT and selecting a functional class for the facility, which will distribute the traffic through the day according to a standard distribution for that functional class.

The next tab in the *Delay* input screen is the *WZ Schedule* (Work Zone Schedule) tab:



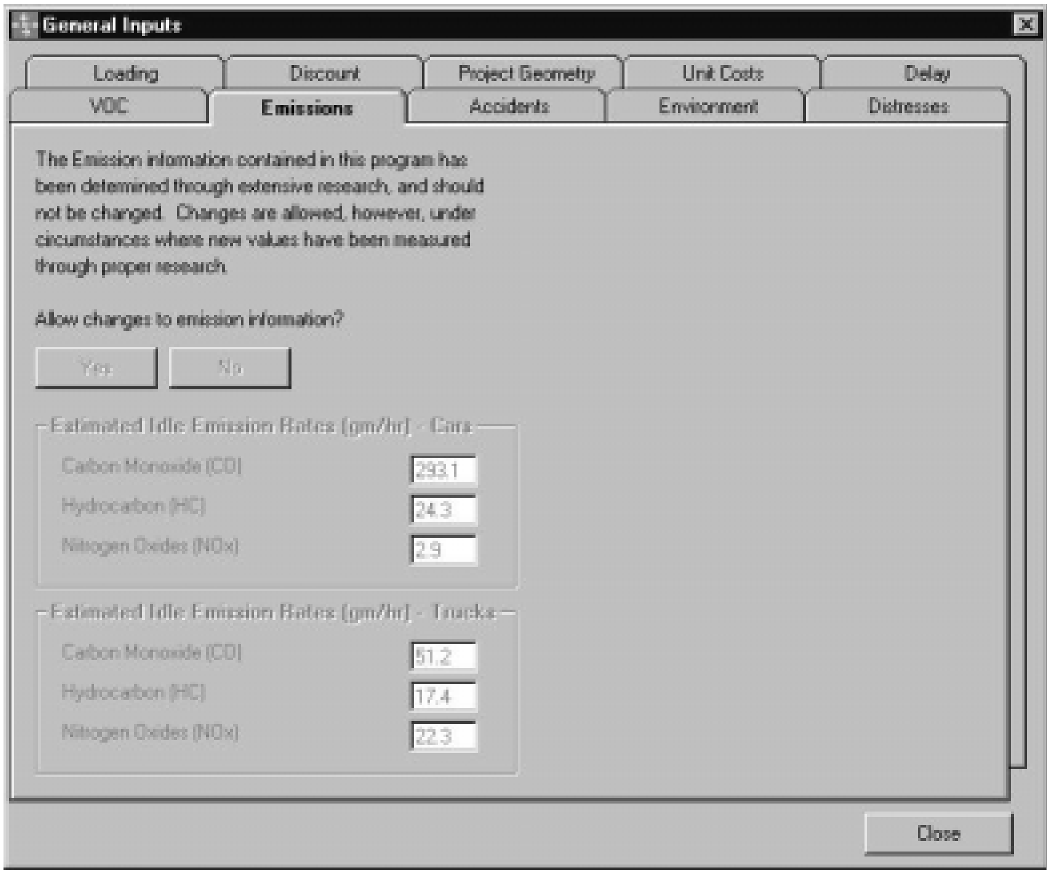
This is where the user enters the time that the traffic control (lane closures, crossovers, etc.) is set up and taken down, in military time (or hundreds of hours). The time that constructions work starts and ends is also required in this screen.

The next *General Inputs* tab is the *VOC* (Vehicle Operating Costs) tab:



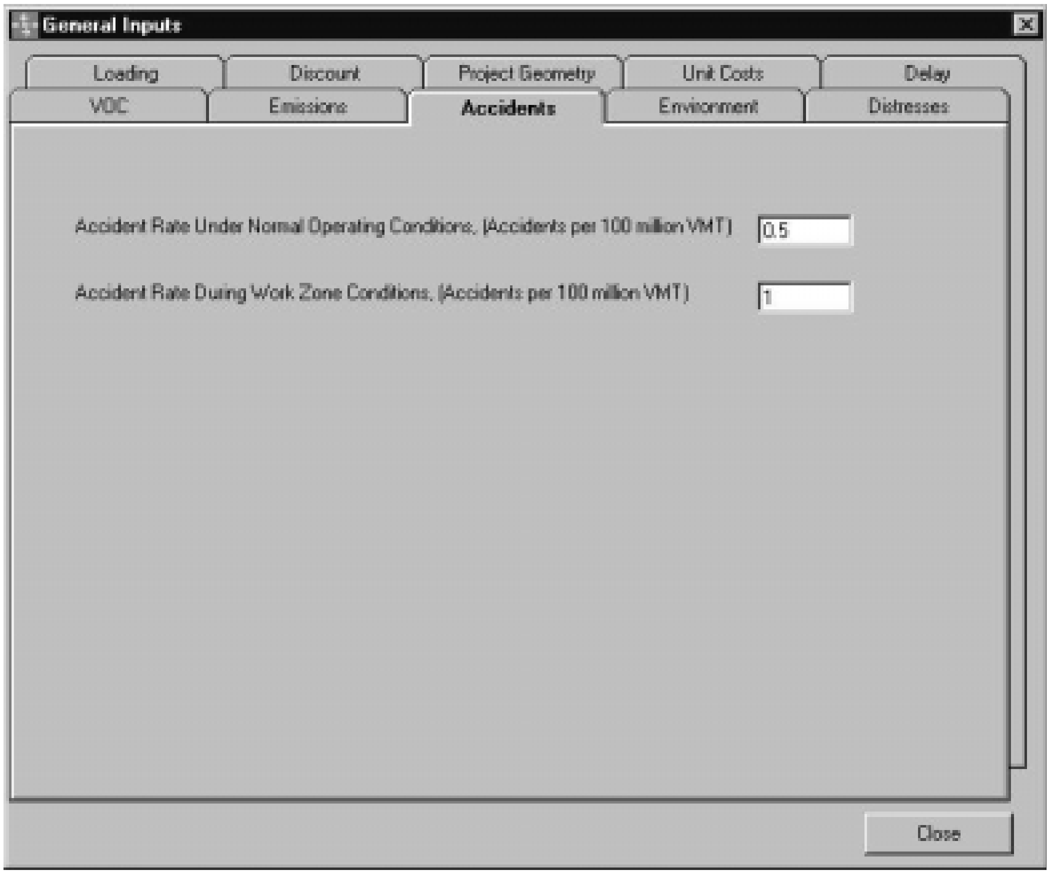
The costs of fuel, tires, vehicles, and time need to be specified here, for both cars and trucks. The average price for a quart of motor oil is also required.

The next input screen is the *Emissions* tab:



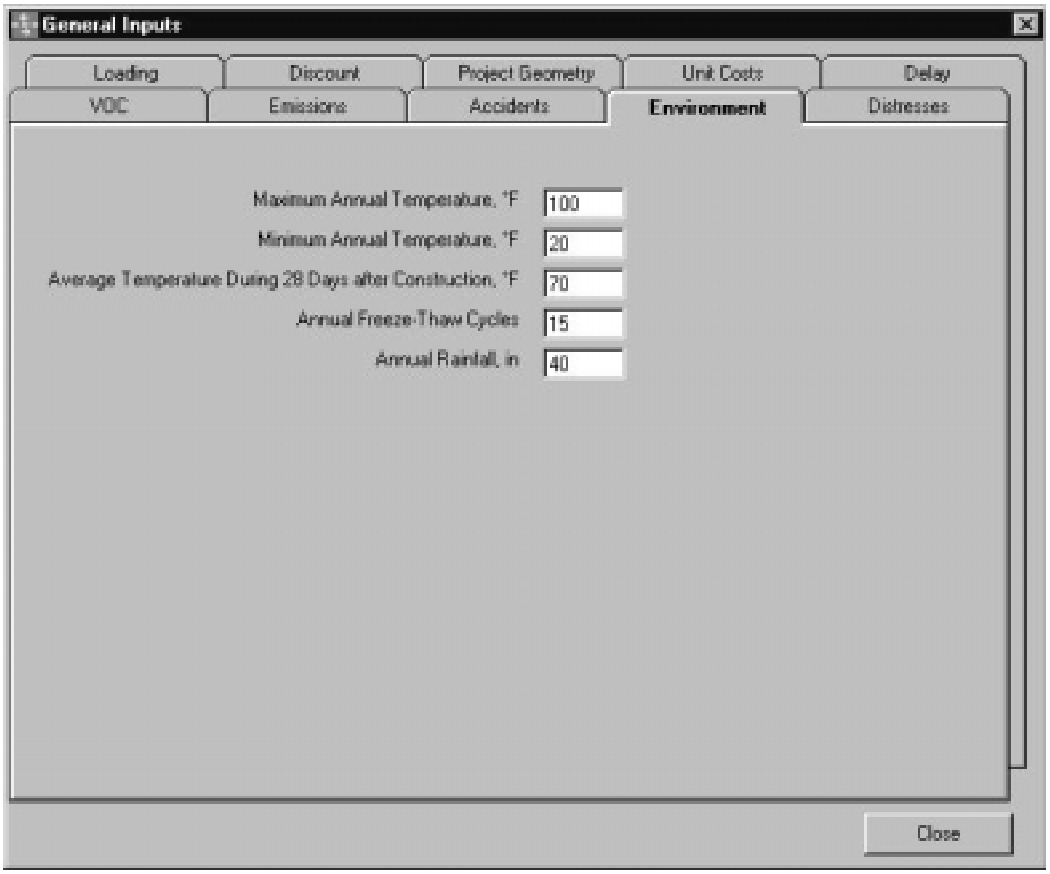
This information on this screen is not available to be changed in this version of the program, but may become accessible in future versions. The values listed on this screen may also change if more research is done on the topic of emissions from cars and trucks. For this version, the default values shown should be adequate for the analysis, since there is no direct "cost" that can be associated with automobile emissions, besides the direct environmental effect of the emissions themselves.

The next input tab is the *Accidents* tab:



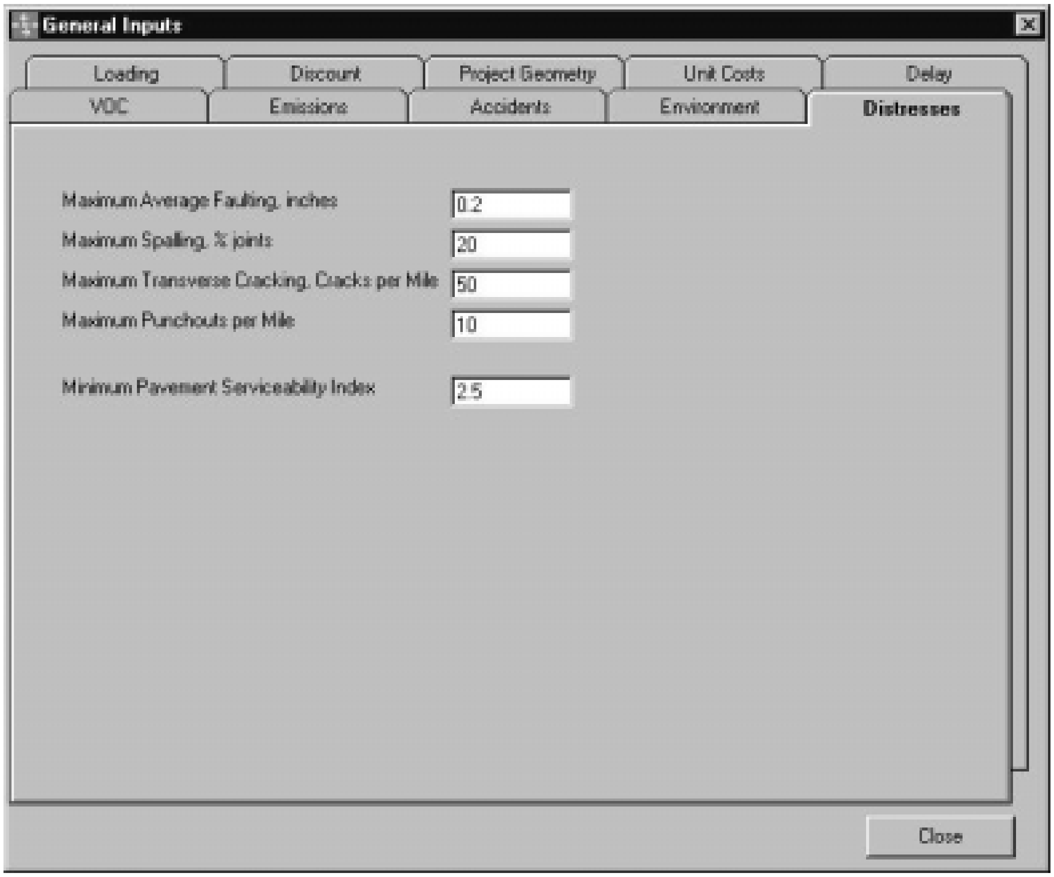
This screen is used to input the accident rates (accidents per 100 million vehicle-miles-traveled) for normal operating conditions, as well as for work zone (construction) conditions.

The next tab is *Environment* tab:



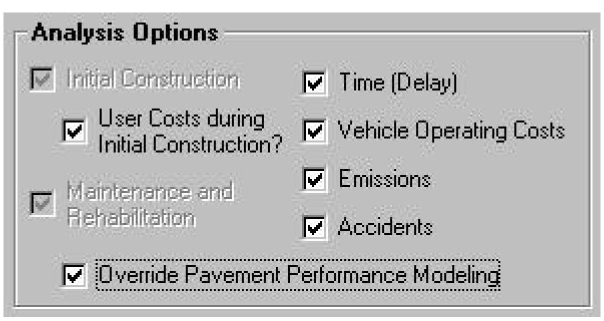
This screen requires the user to input the environmental/weather conditions that the pavement will most likely be subjected to over the analysis period. The maximum and minimum annual temperatures must be specified in degrees Fahrenheit, as well as the average temperature during the 28 days after construction. The number of annual freeze-and-thaw cycles and the inches of annual rainfall expected both need to be entered on this screen as well. All of these inputs are used to help predict the performance of the pavement and its reaction to changes in the environment (i.e., cracking, faulting, spalling, etc.).

The next screen, the *Distresses* tab, is the last of the General Inputs tabs:

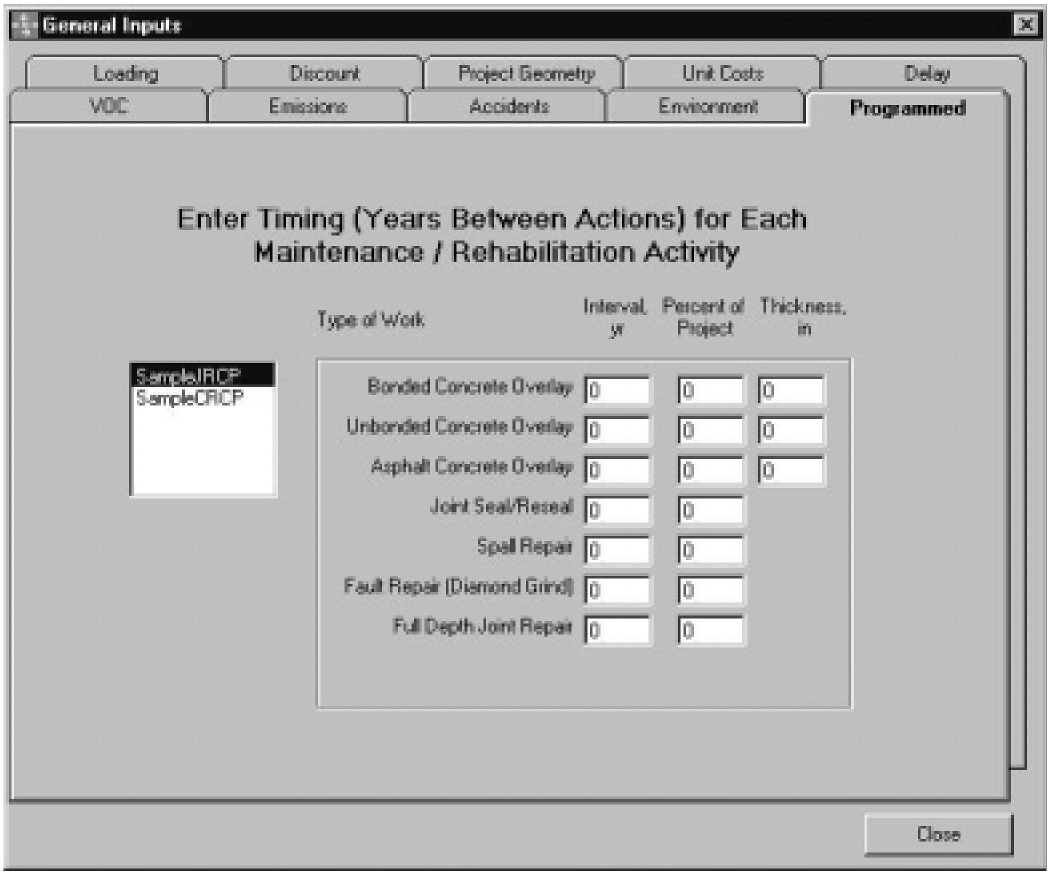


This screen requires the user to input the distress limits for the project. If one of the performance measures exceeds its respective limit [or drops below in the case of Pavement Serviceability Index (PSI)], the program will trigger a rehabilitation option (overlay).

This screen will not show up, however, if the *Override Pavement Performance Modeling* button is selected on the main analysis screen:

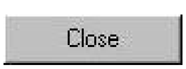


In this case, the program will not use performance equations to predict how well (or badly) the pavement performs, which triggers overlays. Instead, this option replaces the *Distresses* form with the *Programmed* tab:



In this input form, the user specifies exactly when overlays and major rehabilitation strategies are to occur, as well as how much of the project is affected, and thicknesses of the overlays. This process needs to be done for each alternative; on the left side of the screen is the alternative selection box, which highlights the current one being modified.

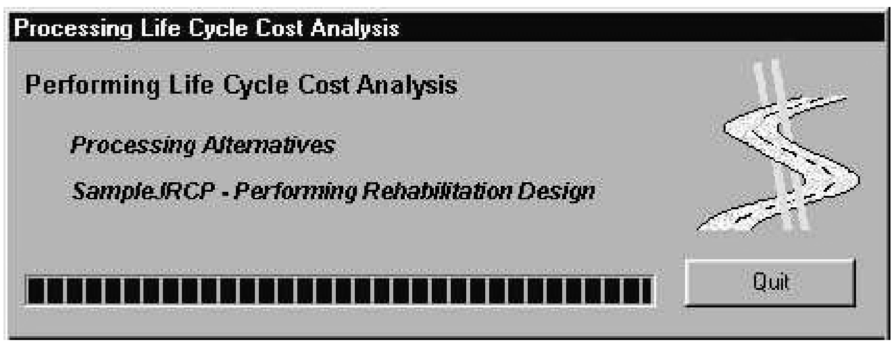
Once either of these methods for determining overlay action has been selected and specified , the *Close* button can be clicked at the bottom of the *General Inputs* window:



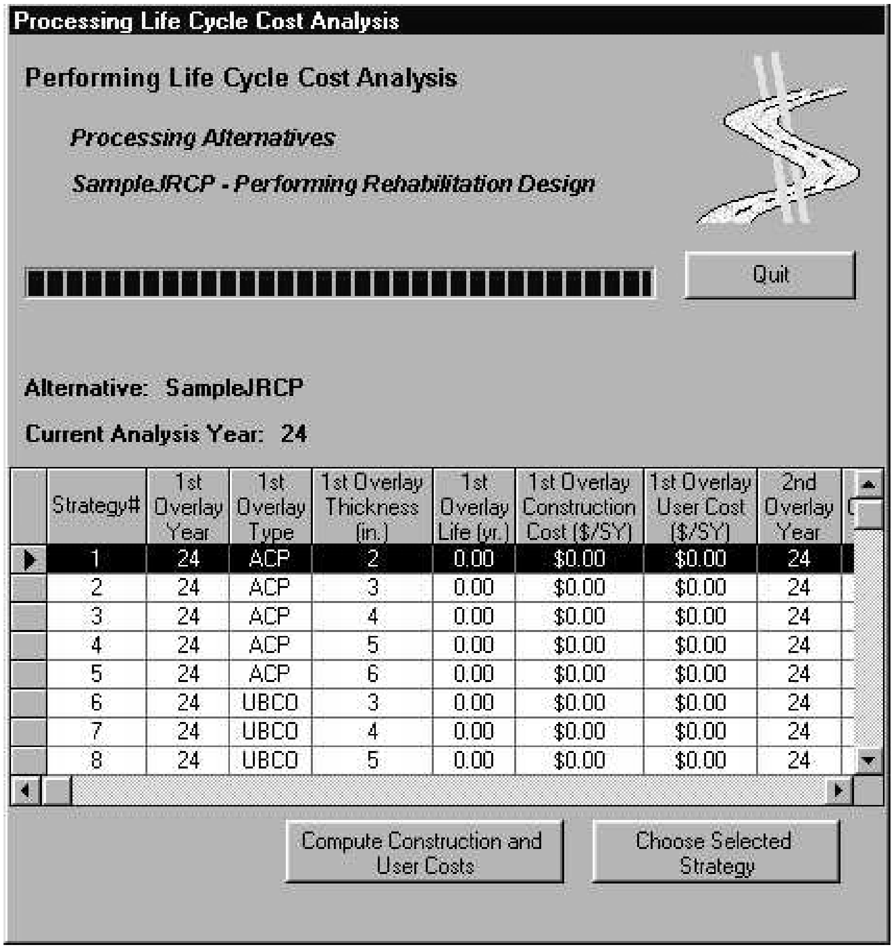
SECTION 5. RUNNING THE ANALYSIS

Once all of the input values have been specified, the life cycle cost can be calculated for each alternative. To do this, push the Begin Analysis button at the bottom of the main analysis screen:

Once this button is pushed, the following screen will pop up:



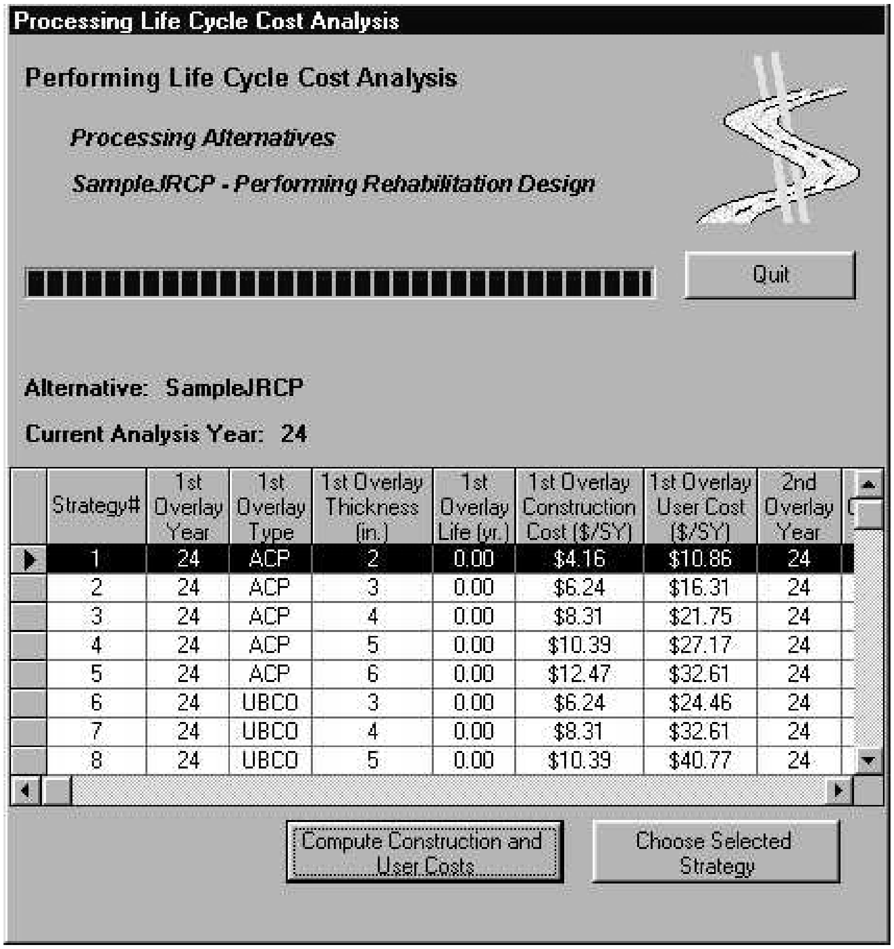
This window shows the status of the analysis being performed. Once the rehabilitations designs are found, the following window will show up:



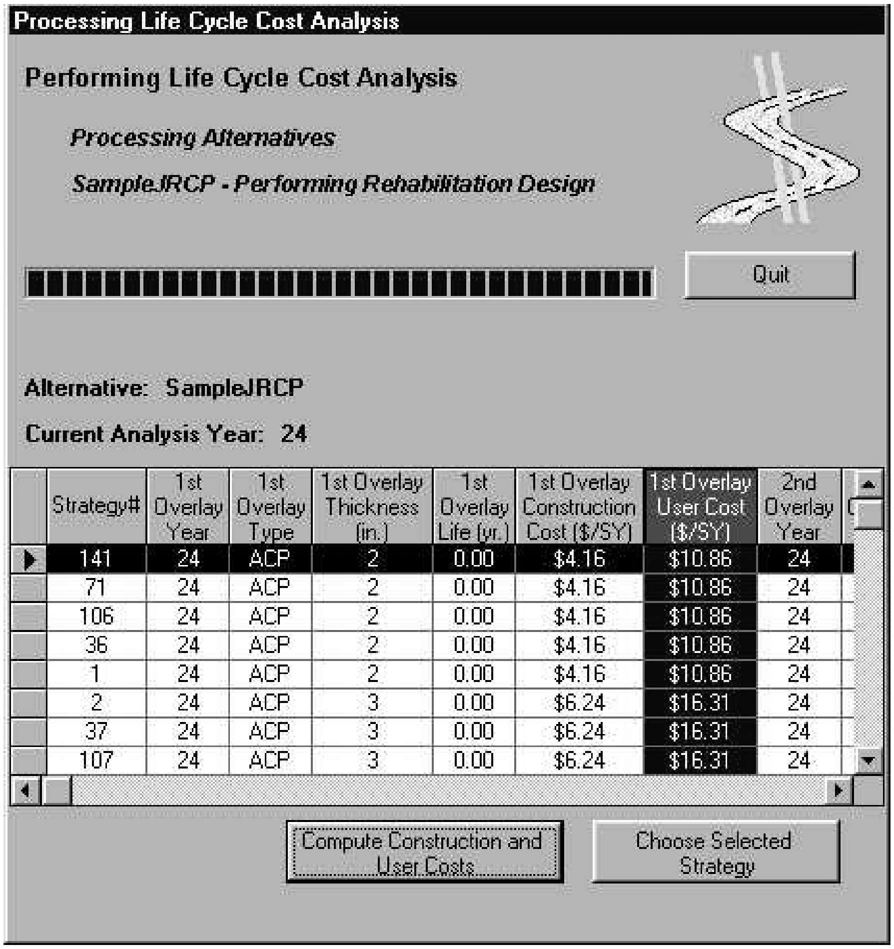
Strategy#	1st Overlay Year	1st Overlay Type	1st Overlay Thickness (in.)	1st Overlay Life (yr.)	1st Overlay Construction Cost ($/SY)	1st Overlay User Cost ($/SY)	2nd Overlay Year
1	24	ACP	2	0.00	$0.00	$0.00	24
2	24	ACP	3	0.00	$0.00	$0.00	24
3	24	ACP	4	0.00	$0.00	$0.00	24
4	24	ACP	5	0.00	$0.00	$0.00	24
5	24	ACP	6	0.00	$0.00	$0.00	24
6	24	UBCO	3	0.00	$0.00	$0.00	24
7	24	UBCO	4	0.00	$0.00	$0.00	24
8	24	UBCO	5	0.00	$0.00	$0.00	24

This screen shows the various possible overlay strategies found by the program. The next step is to press the *Compute Construction and User Costs* button:

This will calculate the construction costs as well as the user costs associated with each of the 175 possible overlay strategies, filling in the table with the appropriate values:



The next step is to sort the overlay strategies, which is done simply by pressing the column header (label) by which you want to sort the strategies. For example, pressing the *1st Overlay Construction Cost [$/SY]* column label will sort all 175 overlay designs according to that column. Likewise, this can be done with the *1st Overlay User Cost [$/SY]* column label:

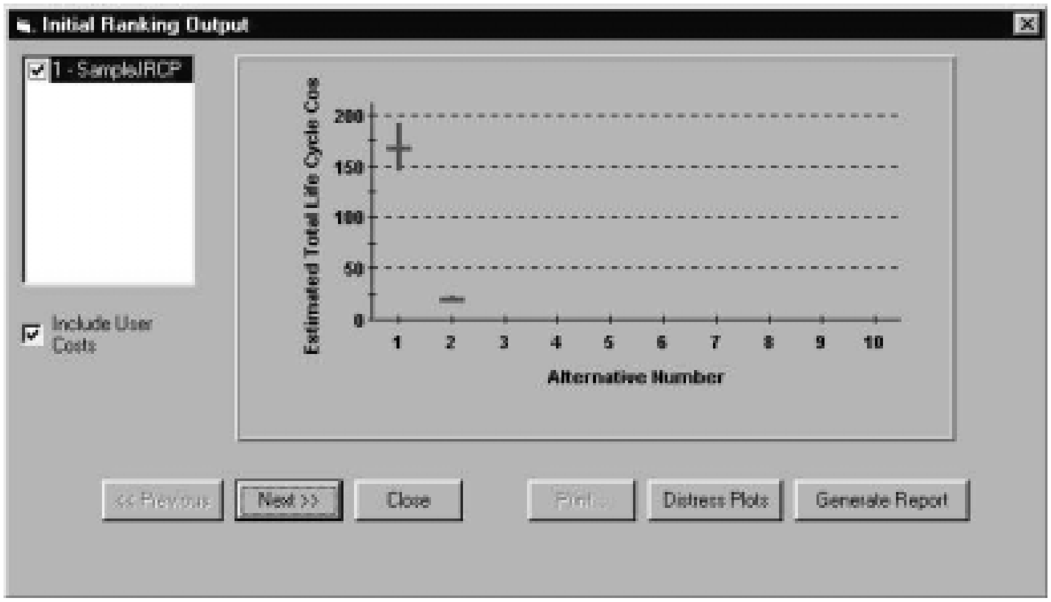


The next step entails selecting the **desired overlay strategy** and then proceeding with the analysis. Click once on the preferred overlay strategy row in the table, and then continue by pressing the *Choose Selected Strategy* button:

The analysis will proceed to the next alternative, or if it was the last one, the output screen will show up.

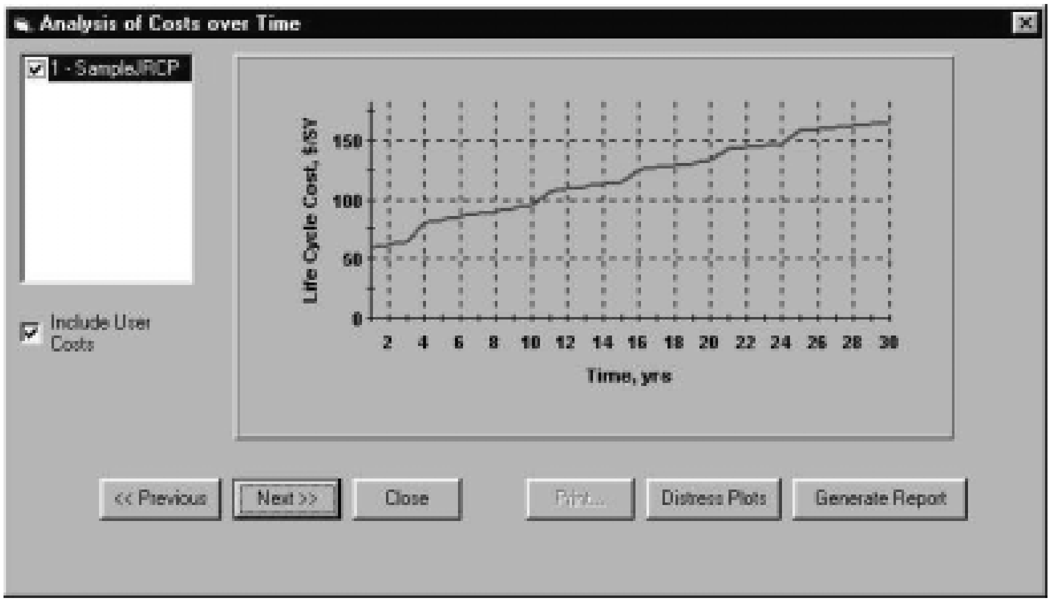
SECTION 6. VIEWING AND INTERPRETING RESULTS

Once overlay options have been selected for all the alternatives in the file, the following screen will be brought up:



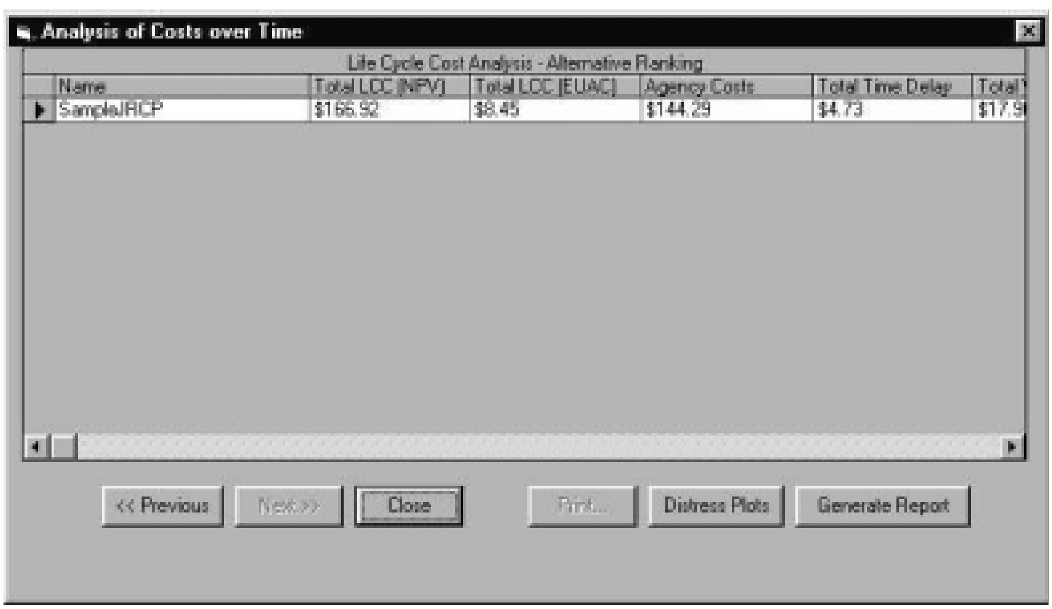
On the left is the list of alternatives. The total life cycle cost for each alternative is plotted in the chart on the right, with error bars extending above and below the value, the length of which are determined by the coefficient of variance (COV) of the analysis. One interesting thing to examine is the **effect** that **User Costs** have on the **Total LCC**. Click and unclick the checkbox on the left, *Include User Costs*, and see the changes resulting on the graph.

Pressing the *Next* button will bring up the following screen:



This screen shows the Life Cycle Cost per square yard of pavement, for each individual alternative, plotted for the analysis period / life of the pavement. The *Include User Costs* checkbox will also have an effect on this plot.

Pressing the *Next* button again will bring up this screen:



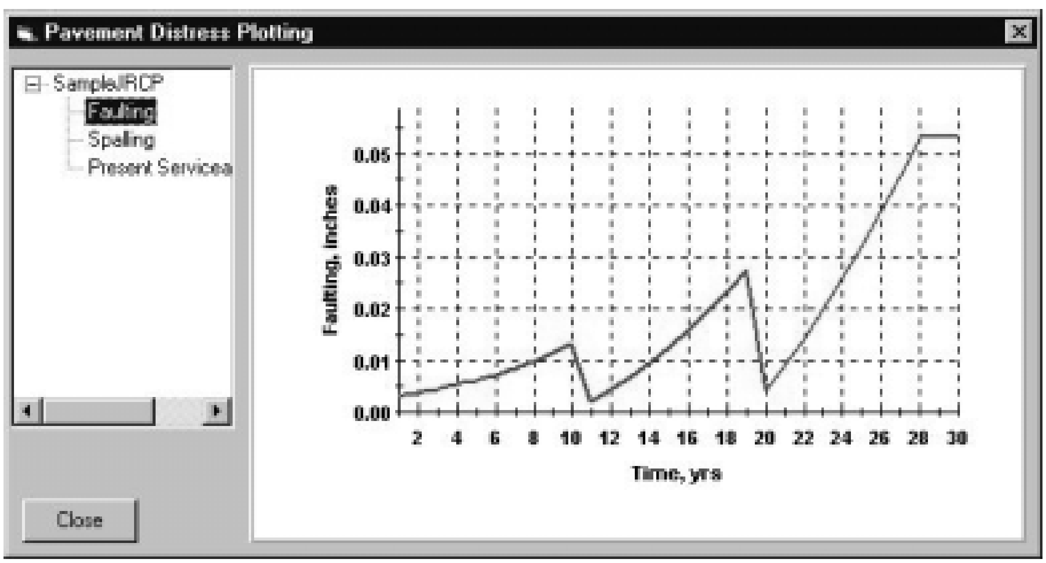
This window contains a table of all the alternatives, with their respective:

(1) Total Life Cycle Cost (LCC) in terms of Net Present Value (NPV)

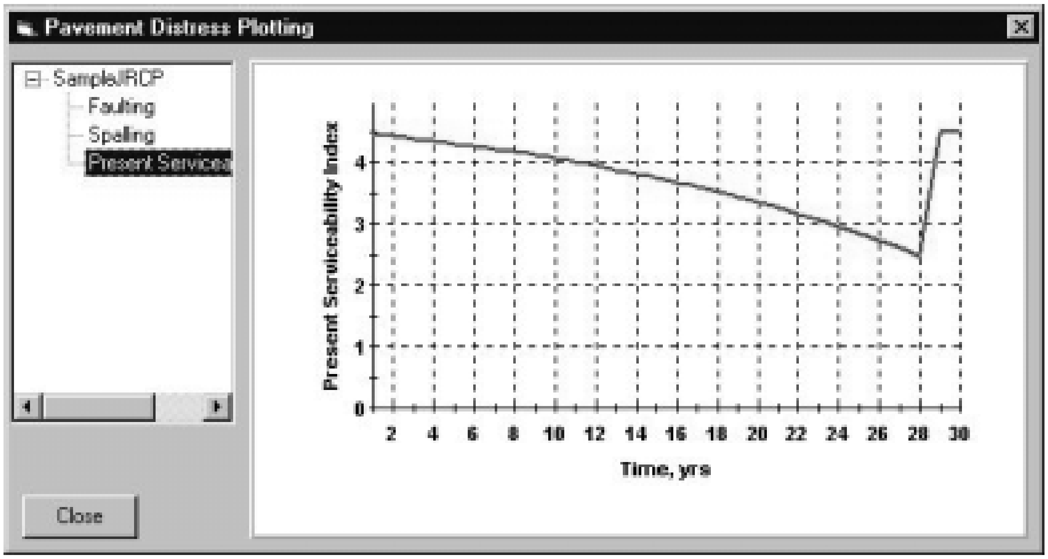
(2) Total LCC in terms of Equivalent Uniform Annualized Cost (EUAC)
(3) Agency Costs – costs paid directly by the agency / owner of the project
(4) Total Time Delay – additional costs paid indirectly by the road users due to added delay during work zones / periods of construction
(5) Total VOC's (Vehicle Operating Costs) – additional costs of operating vehicles during work zones / periods of construction
(6) CO Emissions – additional amounts of carbon monoxide in the air due to work zones / periods of construction
(7) Accidents – number of accidents predicted to occur over the life of the project

The next step is to check the distresses predicted to occur in each pavement alternative. To do this, press the *Distress Plots* button:

The following window will show up:



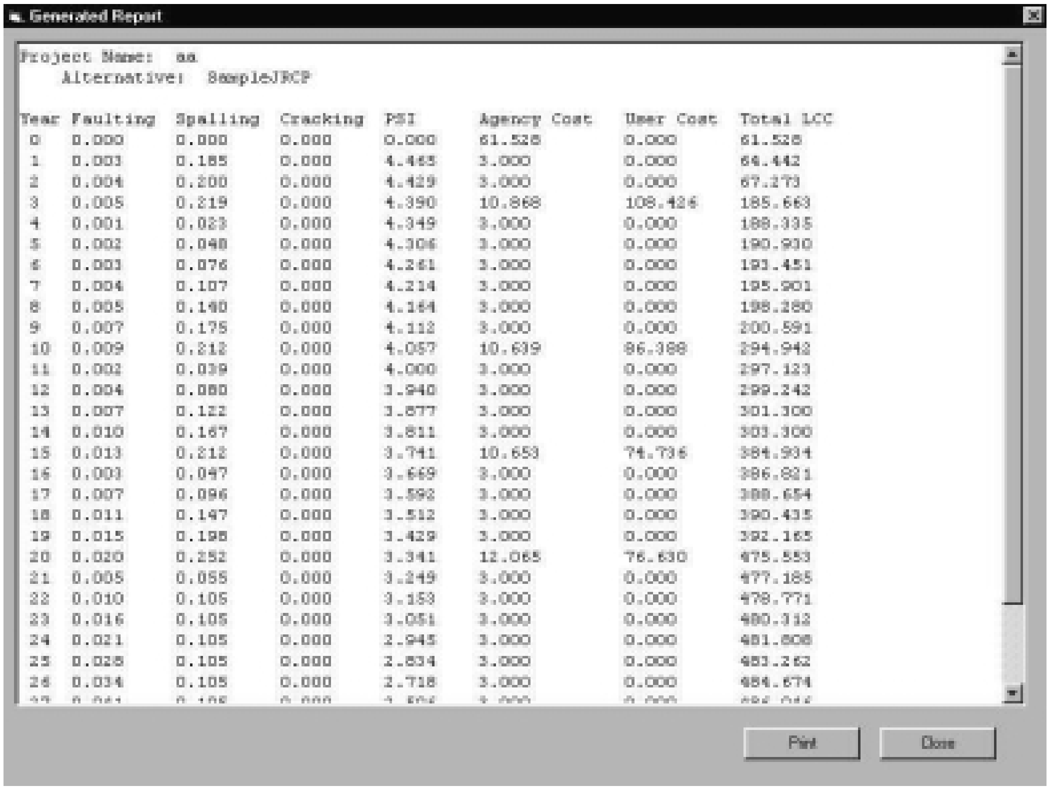
You can also check other distresses and performance measures by clicking on the desired one in the list on the left. For example, Present Serviceability Index (PSI) can be checked:



Once the distresses have been checked, press the *Close* button to go back to the Ranking screen, where the alternatives and their respective LCC's are tabulated.

The next step is to press the *Generate Report* button:

The following window will pop up:



Generated Report

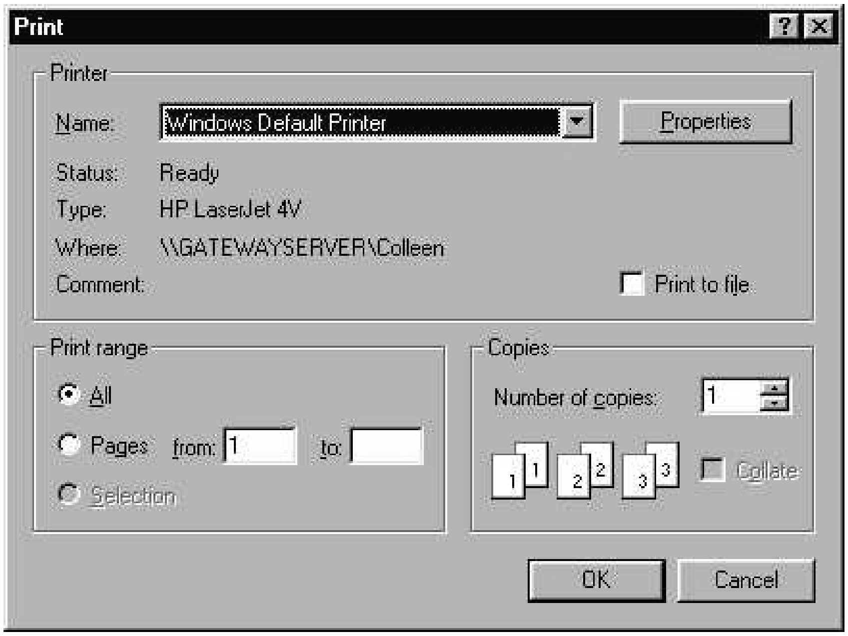
Project Name: aa
Alternative: SampleJRCP

Year	Faulting	Spalling	Cracking	PSI	Agency Cost	User Cost	Total LCC
0	0.000	0.000	0.000	0.000	61.528	0.000	61.528
1	0.003	0.185	0.000	4.465	3.000	0.000	64.442
2	0.004	0.200	0.000	4.429	3.000	0.000	67.273
3	0.005	0.219	0.000	4.390	10.868	108.426	185.663
4	0.001	0.023	0.000	4.349	3.000	0.000	188.335
5	0.002	0.048	0.000	4.306	3.000	0.000	190.930
6	0.003	0.076	0.000	4.261	3.000	0.000	193.451
7	0.004	0.107	0.000	4.214	3.000	0.000	195.901
8	0.005	0.140	0.000	4.164	3.000	0.000	198.280
9	0.007	0.175	0.000	4.112	3.000	0.000	200.591
10	0.009	0.212	0.000	4.057	10.639	86.388	294.942
11	0.002	0.039	0.000	4.000	3.000	0.000	297.123
12	0.004	0.080	0.000	3.940	3.000	0.000	299.242
13	0.007	0.122	0.000	3.877	3.000	0.000	301.300
14	0.010	0.167	0.000	3.811	3.000	0.000	303.300
15	0.013	0.212	0.000	3.741	10.653	74.736	384.934
16	0.003	0.047	0.000	3.669	3.000	0.000	386.821
17	0.007	0.096	0.000	3.592	3.000	0.000	388.654
18	0.011	0.147	0.000	3.512	3.000	0.000	390.435
19	0.015	0.198	0.000	3.429	3.000	0.000	392.165
20	0.020	0.252	0.000	3.341	12.065	76.630	475.553
21	0.005	0.055	0.000	3.249	3.000	0.000	477.185
22	0.010	0.105	0.000	3.153	3.000	0.000	478.771
23	0.016	0.105	0.000	3.051	3.000	0.000	480.312
24	0.021	0.105	0.000	2.945	3.000	0.000	481.808
25	0.028	0.105	0.000	2.834	3.000	0.000	483.262
26	0.034	0.105	0.000	2.718	3.000	0.000	484.674

Print Close

This is a preview of what can be printed. This is also a text file stored in the *Project Files directory*, with the filename the same as the input file, but with an .out extension. For example, if the input file is Sample.lcc, the output file will be Sample.out. This output file can be imported into Excel (or other spreadsheet program), and the values contained therein can be plotted manually.

To print this output file directly, press the *Print* button, and the following standard print window will pop up:



Pressing *OK* will print the output file to the selected printer.

This concludes what can be done with the RPLCCA program.